Evaluating the Human Tactile Response to Haptic Sensations on Textiles

Evaluatie van de menselijke tactiele respons op haptische gewaarwordingen van textiel

Atiyyah Binti Haji Musa

Promotor: prof. dr. ir. L. Van Langenhove
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Doctoral Examination Committee:

Prof. dr. Luc Taerwe (Chairman)	Ghent University, Belgium
Dr. Benny Malengier (Secretary)	Ghent University, Belgium
Prof. dr. ir. Lieva Van Langenhove (Promotor)	Ghent University, Belgium
Prof. dr. Henry Yi Li	University of Manchester, United Kingdom
Assoc. prof. dr. Mohd Rozi Ahmad	Universiti Teknologi MARA, Malaysia
Dr. Mohammad Abu Rous	Lenzing AG, Austria
Dr. ir. Lode Daelemans	Ghent University, Belgium

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The hardest arithmetic to master is that which enables us to count our blessings.

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Atiyyah Musa
Ghent, Summer 2019

To

Abah & Umi

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Summary

If you can't explain it simply, you don't understand it well enough.

Albert Einstein

Being comfortable with the fabrics that we are wearing is one of the elements of satisfaction in life. Hence, fabric comfort needs to be quantified in order to understand the factors that make it comfortable. The evaluation of comfort is often related to ambiguity and subjectivity. Nevertheless, several objective measurement tools and methods have been introduced and in recent time, a device called Fabric Touch Tester (FTT) was commercialized. Therefore, this study employs FTT as the device under focus to measure the tactile comfort of fabrics. FTT is a single device that measures several fabric handle properties within its four modules i.e. bending, compression, thermal and surface, and computes main comfort indices i.e. smoothness, softness and warmth, as well as global indices total hand and touch. Due to the fact that the device is new and there is a lack of studies pertaining to it, the reliability of the device to carry out the handle measurement must be confirmed and the validity of the models should be tested with various types of fabrics and needs to be backed-up by human assessment results.

Hence, the study aims to evaluate human tactile response to haptic sensations on textiles, particularly on clothing fabrics, through analysis on subjective and objective measurement of fabric handle. Taking tactile comfort as the scope in this study, the key objective is to determine the suitability and reliability of the latest objective measurement tool, i.e. FTT, to measure fabric handle properties and make prediction on fabric comfort, based on the measurements that have been made. The development of comfort models for FTT and also other devices depends on the results from human assessment. The actual data from humans serves as the basis to generate the predictive comfort models. Knowing the importance of human assessment to provide data for the objective measurement tools, a comprehensive approach to assess the handle of a high number of fabrics, particularly to deter the human error factors caused by

fatigue and loss of concentration, is required. Thus, the work extends to investigate the approach on human assessment of fabric handle and suggests improvements on the methods. Furthermore, the comfort models from various methods e.g. statistical, neural network and fuzzy logic, are analysed and discussed. The understanding on the current state of the field and a thorough analysis on the advantages and drawbacks of the models contributes to the development of the new models.

The work is presented within six chapters of this thesis. Chapter 1 presents the overview and general introduction of the topic. In Chapter 2, an investigation on FTT fabric indices is reported and Chapter 3 covers the investigations made on subjective touch evaluation. Next, Chapter 4 conveys literature pertaining to predictive comfort models and presents the initial work on a biomechanical model. Then, Chapter 5 captures the work on the investigation of FTT comfort models which leads to the suggestion of new models which consequently need to be validated with actual data from human panels. Lastly, in Chapter 6, the overall conclusion on the work and also the recommendation on further works are mentioned.

The research confirms that the FTT is a comprehensive device that can measure the handle properties of fabrics in a fast and easy way. An investigation on the single FTT fabric indices found that the FTT measurements are associated with the standard or common methods, as given by high correlation values, despite some differences observed in the principle of measurement of both methods. However, the FTT prediction on the comfort properties i.e. smoothness, softness and warmth do not precisely conform to what humans feel. Hence, new models are constructed which proved a better prediction for the said comfort properties, specifically smoothness and softness. Smoothness model SMF 1 which is derived from the full FTT data set consists of five terms in which surface roughness indices i.e. SRA and SRW dominate the first two terms. For smoothness, the mean-derived model SO 1 is chosen as the best model. SO 1 picks-up nine terms, basically from all the modules, but the main terms are from the bending module i.e. BW and BAR. Despite the high fitting of the models with the actual data in the original dataset, warmth models remain invalid when they are tested with other sets of fabrics, indicating a lack of understanding or validity of the warmth testing.

This research also suggests new adapted protocols for the improvement on human evaluations for a large set of fabrics. As the comfort prediction of the device are made depending on the input from the human data, the suggested improvements are significant. In the proposed way, the large set of fabrics are split over several batches, each of 10 samples at most. The method to select the panel members, link the results obtained in different sessions and normalize the data are discussed. Good agreement was found between the panel members for fabric smoothness and softness but the warmth of the fabrics was judged differently as shown by high disagreements between panel members. The protocols can trigger the future possibilities for inter-laboratory assessment to be used across institutions. By this means, diversified type of fabrics can be evaluated by larger panels located worldwide, provided the panel accuracy is verified beforehand, leading to more meaningful results.

The concept of simultaneous tactile measurement of FTT within one single device is an important achievement in the field of haptics. Nevertheless, improvements on FTT in a future version would be welcomed especially with a better accuracy and friction testing, and improved ability to handle diversified textiles. Further work in this field could include the development of prediction models using advanced methods e.g. fuzzy and neural networks, upon the understanding on the factors that govern the tactile behaviour through the developed statistical model. Other than that, biomechanical modelling on textile-skin interaction is widely open for exploration as it is still at early stage which is too early to forecast on its ability, although the potential is promising.

We conclude that in this research work, evaluations on tactile response to haptic sensation on textiles have been made by employing subjective and objective methods. Improvement on the methods are obtained. Nonetheless, despite the huge and rigorous effort that has been contributed for this thesis, there is much more research that will be needed before fabric handle will be fully understood.

Samenvatting

Als je het niet eenvoudig kunt uitleggen, begrijp je het niet goed genoeg.

Albert Einstein

Comfortabel zijn met de stoffen die we dragen, is een van de elementen van voldoening in het leven. Vandaar dat het comfort van de stof moet worden gekwantificeerd om de factoren te begrijpen die het comfortabel maken. De evaluatie van comfort heeft vaak te maken met ambiguïteit en subjectiviteit. Niettemin zijn verschillende objectieve meetinstrumenten en -methoden geïntroduceerd, zo werd sinds enkele jaren een toestel genoemd de Fabric Touch Tester (FTT), op de markt gebracht. Daarom wordt in deze studie gebruik gemaakt van de FTT als het apparaat waarop wordt scherpgesteld om het tactiele comfort van stoffen te meten. FTT is een enkel apparaat dat verschillende greepeigenschappen meet binnen zijn vier modules, namelijk buigen, compressie, thermisch en oppervlakte eigenschappen. De FTT berekent verder ook nog hoofdcomfortindices, dat wil zeggen gladheid, zachtheid en warmte, evenals de globale indices totale hand (total hand) en totaal aanvoelen (total touch). Vanwege het feit dat het apparaat nieuw is en er nog een gebrek aan studies over zijn, moet de betrouwbaarheid van het apparaat voor het uitvoeren van de meting van greepeigenschappen worden bevestigd en moet de validiteit van de modellen worden getest met verschillende soorten stoffen alsook worden ondersteund door beoordelingstesten testen met menselijke panelleden/experten.

Vandaar dat deze studie de menselijke tactiele respons op haptische gewaarwordingen van textiel, in het bijzonder op kledingweefsels, analyseert door middel van analyse van subjectieve en objectieve metingen van de handgreep en het aanvoelen van stoffen. Gelet op tactiel comfort als de focus van het onderzoek, is het belangrijkste doel van de studie de geschiktheid en betrouwbaarheid te bepalen van het nieuwste objectief meetinstrument, d.w.z. de FTT, om de eigenschappen van de handgreep van textiel te meten en voorspellingen te doen over het comfort van de stof op basis van de metingen die zijn gedaan. De ontwikkeling van comfortmodellen voor FTT en ook andere apparaten is afhankelijk van de resultaten van menselijke beoordeling. De feitelijke gegevens van de mens dienen als basis voor het genereren van de voorspellende comfortmodellen. Gelet op de belangrijkheid van de menselijke beoordelingen om gegevens te verstrekken voor de objectieve meetinstrumenten, is een uitgebreide aanpak nodig om de greep van een groot aantal weefsels te beoordelen. Deze aanpak dient met name de menselijke foutfactoren te ontmoedigen die worden veroorzaakt door vermoeidheid en concentratieverlies. Het werk strekt zich daarom uit tot het onderzoeken van de bepaling van de menselijke beoordeling van handgreep van stoffen en suggereert verbeteringen in de methoden. Verder worden de comfortmodellen van verschillende werkwijzen, b.v. statistisch, neuraal netwerk en fuzzy logic, geanalyseerd en besproken. Het inzicht in de huidige stand van zaken en een grondige analyse van de voor- en nadelen van de modellen dragen bij aan de ontwikkeling van de nieuwe modellen.

Het werk wordt gepresenteerd binnen zes hoofdstukken in dit proefschrift. Hoofdstuk 1 presenteert het overzicht en de algemene introductie van het onderwerp. In Hoofdstuk 2 wordt een onderzoek naar FTT-weefselindices gerapporteerd en Hoofdstuk 3 behandelt het onderzoek naar subjectieve aanrakingsevaluatie. Vervolgens geeft Hoofdstuk 4 literatuur weer die betrekking heeft op voorspellende comfortmodellen en presenteert het de eerste resultaten van een biomechanische model. Vervolgens beschrijft Hoofdstuk 5 het onderzoek naar FTT-comfortmodellen, wat leidt tot de suggestie van nieuwe modellen welke dan gevalideerd moeten worden met feitelijke gegevens aangeleverd door menselijke panelleden. Ten slotte wordt in Hoofdstuk 6 de algehele conclusie over het werk en ook de aanbeveling over verdere werken gegeven.

Het onderzoek bevestigt dat de FTT een uitgebreid apparaat is dat de greepeigenschappen van stoffen op een snelle en eenvoudige manier kan meten. Een onderzoek naar de afzonderlijke FTT-weefselindices wees uit dat de FTT-metingen zijn gekoppeld aan de standaardmethoden of aan veelgebruikte methoden, zoals gegeven door hoge correlatiewaarden, ondanks enkele verschillen die aanwezig zijn in het meetprincipe van beide methoden. Evenwel voldoet de FTT-voorspelling van de comforteigenschappen, d.w.z. gladheid, zachtheid en warmte, niet precies aan wat mensen voelen. Vandaar dat nieuwe modellen zijn geconstrueerd die een betere voorspellende waarde voor de genoemde comforteigenschappen, in het bijzonder gladheid en zachtheid, bewezen hebben. Gladheidsmodel SMF 1 dat is afgeleid van de volledige FTT-gegevensverzameling bestaat uit vijf termen waarin oppervlakteruwheidindices, d.w.z. SRA en SRW, de dominerende zijn. Voor de zachtheid wordt het op basis van gemiddelden afgeleide model SO 1 gekozen als het beste model. SO 1 omvat negen termen, in feite van alle modules, maar de eerste twee termen in de lijst zijn van de buigmodule, d.w.z. BW en BAR. Ondanks de hoge pasvorm van de modellen met de feitelijke gegevens in de oorspronkelijke dataset, blijven warmtemodellen ongeldig wanneer ze worden getest met andere sets weefsels, wat wijst op een gebrek aan begrip of validiteit van de warmetests.

Dit onderzoek suggereert ook nieuwe aangepaste protocollen voor de verbetering van menselijke evaluaties bij een groot aantal weefsels. Omdat de comfortvoorspelling van het apparaat wordt gemaakt afhankelijk van de input van de menselijke gegevens, kan de invloed van de voorgestelde verbeteringen aanzienlijk zijn. Op de voorgestelde manier wordt het grote aantal stoffen verdeeld over verschillende partijen, elk maximaal 10 monsters. De methode om de panelleden te selecteren, de resultaten van verschillende sessies te koppelen en de gegevens te normaliseren, wordt besproken. Goede overeenstemming werd gevonden tussen de panelleden voor de gladheid en zachtheid van de stof, maar de warmte van de stoffen werd anders beoordeeld, zoals blijkt uit de grote meningsverschillen tussen de panelleden. De protocollen kunnen toekomstige mogelijkheden creëren voor interlaboratorium beoordeling van textiel voor gebruik in alle instellingen. Op deze manier kan een gediversifieerde soort stoffen worden geëvalueerd met panelleden verspreid over de hele wereld, op voorwaarde dat de nauwkeurigheid van de panelleden van tevoren wordt geverifieerd, noodzakelijk om te garanderen dat de resultaten zinvol zullen zijn.

Het concept van simultane tactiele meting door de FTT binnen één apparaat is een belangrijke prestatie op het gebied van haptische gewaarwording. Desalniettemin zouden verbeteringen van FTT in toekomstige versies worden verwelkomd, vooral dan een betere nauwkeurigheid en betere wrijvingstest, alsook de afhandeling van meer gediversifieerd textiel. Verder werk binnen het onderzoeksdomein kunnen de ontwikkeling van voorspellingsmodellen omvatten met behulp van geavanceerde methoden, b.v. fuzzy en neurale netwerken, op basis van de factoren die het tactiele gedrag bepalen via het ontwikkelde statistische model. Daarnaast is biomechanische modellering op textiel-huid interactie wijd open voor exploratie omdat het nog in een vroeg stadium is, te vroeg om te voorspellen wat het belang zal zijn, hoewel het wel al duidelijk is dat het potentieel veelbelovend is.

We besluiten dat in dit onderzoek de menselijke tactiele respons op haptische gewaarwordingen van textiel is onderzocht door gebruik te maken van subjectieve en objectieve methoden. Verbeteringen aan de methoden werd bekomen. Ondanks de enorme en rigoureuze inspanningen die aan dit proefschrift zijn geleverd, is er echter nog veel meer onderzoek nodig voordat de menselijke beoordeling van handgreep van stoffen volledig zal begrepen zijn.

1

Introduction

If you can't stand the fatigue of study, you will feel the poignant of stupidity.

Imam Syafi'i

This chapter presents an overview of the research topic starting from a broad definition of comfort, branches of comfort studies, thus leads to the main topic of tactile comfort for fabrics. A review on the past and current measurement methods for fabric tactile comfort is included which brought to identification of problem statements and research questions. Then, the aim and objectives of this study are also identified and the thesis flow is outlined.

1.1 Introduction

Every day, we deal with textiles around us. Starting in the morning when we wake up from a comfy bed with silky bedsheet of 100% combed cotton, slip on polyester microfibers furry slippers, brush our teeth with a nylon bristles toothbrush, put on a water absorbent towel after shower, dress up in sleek suits, sip some tea which comes from a nonwoven teabag, and drive a car of which even the tyres have components made of textiles. Our life revolves around textiles. Those are just some common uses that we may or may not have noticed (see Figure 1-1). For how significant it is to us, we always want the best of it; it must fit its purpose, look good and we are concerned on how textiles can make us feel good.

Clothing is an essential necessity for humans. People seek for garments that can make them comfortable, besides the aesthetic feel that the garments offer. For instance, winter clothing is supposed to protect the body from coldness of winter, but not only it should make the wearer feel comfortable while wearing, it must also not make the skin underneath unbreathable. Also, it should not be too heavy as that could bring an uncomfortable feel to the wearer. A study in the feel of fabric or clothing comfort often deals with the end users; their perceptions and needs.

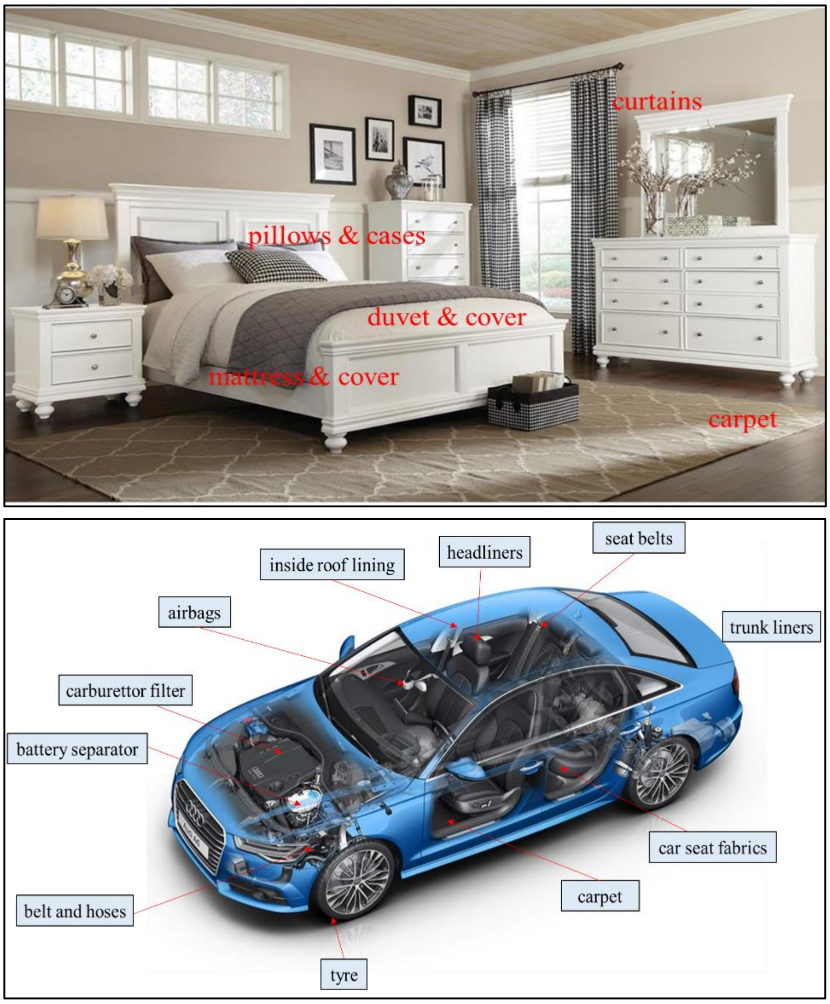

Figure 1-1 Some examples of various textiles around us; top: textiles in a bedroom, bottom: textile in a car

Clothing comfort is often recognizable in the presence of discomfort. It is true that we seldom realize what we feel all right until we experience something that is not right. Hence, an easy interpretation of comfort as ‘the absence of discomfort or the neutral state in which an individual experiences no pain or discomfort’ makes sense (Slater, 1977). It is also defined as ‘a pleasant state of physiological, psychological, and physical harmony between a human being and the environment’ (Barker, 2007; Yaning, 2015). In clothing, various stimulant can trigger the comfort of a garment either from *physical, physiological or psychological* factors. Thus, a balance of these three aspects within the human and environment would create a comfort sensation.

With regard to the **physical** aspects, it involves the interaction of the environment and the motions of human body. This is associated with the physical stimuli such as mechanical interaction between clothing and the body e.g. compressibility, flexural rigidity and friction, acoustic, optics, thermodynamics etc. (Li & Wong, 2006; Yaning, 2015). However, for **physiological** aspects, it involves the process in the human body to keep the body alive and well-functioned which involves the aspects of thermoregulation, heart rate, body temperature, sweating and evaporation etc. On the other hand, **psychological** is related to emotional and behavioural responses of a human being which are normally derived from one’s personal taste or instinct, and social environments e.g. cultural influence, social relationship and physical surroundings (Yaning, 2015).

After putting on a garment, a series of intricate interactive processes is executed that formulate the sensory perception for the garment. These include *physical, physiological, neurophysiological and psychological* processes (Hu, 2006; Li & Wong, 2006). The **physical** process happens in the clothing and the surrounding environment such as heat and moisture transport in clothing and mechanical interaction between clothing and the body which provide the physical signals to the body. Then, the **physiological** process happens in the body e.g. the thermal balance mechanism involving the thermoregulatory responses and dynamic interactions with clothing and environment, thus ensure the physiological status of the body. After that, **neurophysiological** process takes place by a mechanism of the sensory reception system of the body in the skin, eyes, and other organs, in which sensory signals are formulated from the interactions of the body and environments. Lastly, the most complex process happens in the brain i.e. **psychological** process upon receiving the neurophysiological sensory signals. The brain processes the signals then formulates the subjective perception of sensory sensations, also the overall perceptions and preferences by evaluating and weighing various sensory perceptions from past experiences and internal desires (Hu, 2006; Li, 2001; Li & Wong, 2006).

The status of comfort or discomfort is a result of these processes in which the sensory reception system plays a vital role where the sensory organs are the ones that receive the stimulations from the physical stimuli. The stimuli can trigger the five sensory organs hence, the comfort sensation can be further refined to visual comfort (the comfort perceived by sight), auditory comfort (the comfort perceived by hearing), gustatory comfort (the comfort perceived by taste), olfactory comfort (the comfort perceived by smelling), and tactile comfort (the comfort perceived by touch) (Mahar, Wang, & Postle, 2013; Naghizade & Ostadi, 2014). However, gustatory comfort is not applicable and omitted for textile products.

The four comfort sensation i.e. visual, auditory, olfactory and tactile do influence the consumer preference (Kayseri, Özdil, & Mengüç, 2012). Nevertheless, tactile comfort is mostly related to touch perception of the fabrics, compared to the other three. Hence, many studies dealt with tactile comfort which shows a great importance of it as a main contributor in determining the overall comfort of the fabrics.

Tactile comfort in clothing normally refers to the sensations given by the garments or fabrics when they touch the human body. It is affected by the texture of the fabrics which can be contributed by the effect of fibre, yarn, fabric or treatments given to them. The study on determining the prominent sensations of tactile comfort often relates to the research areas of psychophysical and semantics. In order to choose the right vocabulary to explain the texture of the fabrics, researchers have conducted experiments which involved human panel members to evaluate several textures and give meaningful words that can describe the textures (Kawabata, 1980). Another attempt was made by classification method where several materials with different type of textures were presented to the panel members and they were asked to cluster the materials which have similar structures together (Meilgaard, Vance Civille, & Thomas Carr, 2007). The branch of study dealing with touch perception is referred as haptics.

Studies from the previous researchers suggest several tactile sensations which primarily affect the tactile comfort. The sensations include coolness, warmness, moistness, dryness, roughness, smoothness, hardness, softness, stickiness, slipperiness, bulkiness, prickliness etc. (Okamoto, Nagano, & Yamada, 2013). Some of the words used are bipolar characteristics of one another such as coolness and warmness, moistness and dryness, roughness and smoothness, hardness and smoothness and stickiness and slipperiness. Some are related to each other like stickiness/slipperiness to roughness/smoothness, bulkiness to hardness/softness, which can be merged or combined in either one aspect only. Coolness/warmness and moistness/dryness were somehow much inclined to the study in physiological or thermal comfort. Nevertheless, as the skin often reacts to the coolness/warmness sensation of the garments immediately after putting them on the body, these sensations are somehow included as the fundamental tactile sensations (Pan, 2007). During the skin-fabric contact, a transient heat conduction phenomenon occurs where a sensation of warm or cool is felt. Normally, the skin is at a higher temperature than the fabric when it is brought into contact, thus heat flows away from the skin. For roughness/smoothness and hardness/softness, there is no doubt that these are the most influential sensations which lead to tactile comfort.

1.2 Fabric handle

1.2.1 Definition of fabric handle

The studies to measure comfort often deals with fabric hand. Fabric *hand* or *handle* is defined in several ways as reported in the literature. Dawes and Owens (Dawes & Owen, 1971) referred to it as *the sum total of the sensations expressed when a textile fabric is handled by touching, flexing of the fingers, smoothing and so on.* The Textile Institute definition goes as *the subjective assessment the textile material obtained from the sense of touch* (Bishop, 1996; Kayseri et al., 2012) while American Association of Chemists and Colorist (American Association of Textile Chemists and Colorists, 2014) defined it as *the tactile sensations or impressions which arise when fabrics are touched, squeezed, rubbed or otherwise handled.* Ciesielska-Wrobel and Van Langenhove (Ciesielska-Wrobel & Van Langenhove, 2012) give a thorough definition of subjective hand of textile i.e. *The hand of textiles based on the holding of the textile or the smoothing of the textile with the palm is an act of experiencing the textile's thickness and surface, and other textile physical features against the skin of the palm which evokes the impressions related to physical features of the material perceived by the fingers and palm skin receptors and transferred neurologically to the cerebral cortex. The judgement is given after referring to the personal experience of the person who makes this judgement as well as his or her natural skin sensibility.* The mechanical and surface properties of each fabric caused tactile sensations to the skin. These serve as a fingerprint that enable the quantification of fabric handle.

1.2.2 Measurement of fabric handle

The given definitions of fabric handle address the physical assessment by humans which is referred as subjective assessment or interchangeably termed as human assessment. Studies on this topic were pioneered by Binns (Binns, 1926b) in 1926 and continue until this present time. His works provides an early analysis on the judgement of fabric handle by human panels (Binns, 1926b, 1926a, 1934). This kind of human assessment is sometimes called as sensory judgement or psychological assessment in the literatures. Usually, expert panels are given some fabrics and they are requested to evaluate the handle of the fabrics. Rank and rate methods are normally used to quantify the intended fabrics properties in which fabrics are evaluated by giving a rank e.g. from the smoothest to the least smooth, softest to the least soft, etc. in rank method. In rate method, the assessor will need to give a rate from some scales e.g. 1 to 10, based on how smooth or how soft they perceived the fabric. Ranking can also be applied by using pairwise method where all the fabrics are presented to the assessor in pair. For a set of fabrics, all the possible combinations are brought to the assessors to assess, thus the ranking can be determined based on the assessor's choice at the end of the test (Ciesielska-Wrobel & Van Langenhove, 2012; Slater, 1977, 1997). Quantifying the data from human judgement requires standardized procedures and considerations. As humans are complex in nature, the set of procedures are needed at least to control the deviation caused by human factors e.g. visual bias, fatigue etc., towards achieving a highly repeatable results.

In 1930, the pioneering effort on quantifying the mechanical properties of fabrics can be traced back to the work of Peirce, written in one of the most cited research paper entitled 'The handle of cloth as a measurable quantity' (Peirce, 1930b). He initiated the measurement of fabric stiffness and suggested the correlation between this mechanical property to fabric handle. Since then, many attempts were made to develop an objective measurement for fabric properties which somehow overshadowed the focus on the connection of the property to the fabric handle measurement.

Nevertheless, in 1958, in an attempt to identify the underlying interrelationship in fabric handle assessment of several fabrics, Howorth and Oliver applied the multiple factor analysis technique, and they isolated three factors that are responsible for handle i.e. smoothness, softness and thickness, exceeded the other properties including warmth, coarseness and weight for the tested mens' suiting materials (Howorth & Oliver, 1958; Mahar & Postle, 1989). This had become a first step forward in which a set of attributes were recognized as to describe fabric handle preference. Later in 1972, Prof Sueo Kawabata led the formation of the Hand Evaluation and Standardisation committee (HESC) of the Textile Machinery Society of Japan (Kawabata, 1972, 1973). From the analysis on subjective handle assessment of the experts in HESC, he specified three attributes that are mainly associated with fabric handle and referred them as primary hand value (PHV) i.e. Koshi, Numeri and Fukurami or translated as stiffness, smoothness, and fullness-softness, respectively. Another term i.e. total hand value or THV on the other hand is the rank of preference on a scale of 0 (unacceptable) to 5 (excellent) for the particular fabrics tested i.e. winter suits fabrics. This work served as a starting point for his epic invention of an objective measurement system of fabric handle known as Kawabata Evaluation System for Fabrics (KES-F, later upgraded and known as KES-FB), together with his associate, M. Niwa (Kawabata, 1980; Kawabata & Niwa, 1989).

KES-FB is a system for fabric handle evaluation which comprises of four devices that measure fabric mechanical and surface properties. The four devices are classified as KES-FB1 for tensile and shearing, KES-FB2 for bending, KES-FB3 for compression and KES-FB4 for surface friction and variation. These devices possess a low-stress mechanical, physical and surface testing which are suitable for fabrics. Through the measured properties, a series of calculation is imposed to generate the PHV and THV of the fabrics. The equations for the calculations were developed using the multiple linear regression technique to correlate the mechanical measurements data to subjective fabric hand evaluation, and thus provided physical interpretation of test results (Kawabata & Niwa, 1989). This task is made feasible through support of a computer system.

Another remarkable objective measurement system is known as Fabric Assurance by Simple Testing or SiroFAST or simply referred as FAST (De Boos & Tester, 1994). This system is developed by the Division of Wool Technology at the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) (Behera & Hari, 1994; De Boos & Tester, 1994, 2005). The prominent advantage of this device relies on its simplicity in the testing procedures and data interpretation, and it is also cheaper as compared to KES-FB. This system consists of three instruments and a test method; i.e. SiroFAST-1 is a compression meter that measures fabric thickness, SiroFAST-2 is a bending meter that measures the fabric bending length, SiroFAST-3 is an extension meter that measures fabric extensibility, and SiroFAST-4 is a test procedure for measuring dimensional properties of fabric. It is to note that the SiroFAST system includes dimensional stability properties i.e. relaxation shrinkage and hygral expansion, as part of the properties it measures, unlike the KES-FB. The interpretation of the fabric handle performance is obtained through a comparison of a fingerprint plotted based on the measured properties and the control chart, with the help of a computer software. Table 1-1 listed the properties and indices measured and derived from KES-FB and SiroFAST.

Table 1-1 Measured and derived fabric properties by KES-FB and SiroFAST (adapted from Kawabata & Niwa, 1989 and De Boos & Tester, 1994)

KES-FB	**SiroFAST**
Tensile	Fabric weight
LT - Linearity of load/extension curve	Compression
WT - Tensile energy	Fabric thickness at 2 g/cm^2
RT - Tensile resilience	Fabric thickness at 100 g/cm^2
EM - Extensibility at 500 gf/cm	Released thickness at 2 g/cm^2
Bending	Released thickness at 100 g/cm^2
B - Bending rigidity	Fabric surface thickness
2HB - Hysteresis of bending moment	Finish stability
Shearing	Bending
G - Shear stiffness	Bending length
2HG - Hysteresis of shear force at 0.5° shear angle	Tensile
2HGS - Hysteresis of shear force at 5° shear angle	Bending rigidity
Compression	Fabric extensibility
LC - Linearity of compression/thickness curve	Warp extensibility
WC - Compressional energy	Weft extensibility
RC - Compressional resilience	Bias extensibility
Surface	Shear rigidity
MIU - Coefficient of friction	Formality
MMD - Mean deviation of MIU	Dimensional stability
SMD - Geometrical roughness	Relaxation shrinkage
Thickness	Hygral expansion
T - Fabric thickness	
Weight	
W- Fabric weight	

Besides these two systems which are widely utilized until now, a simpler method known as **extraction method** has been reported in several papers. Through this method, the load-displacement curve is obtained and observed when the fabric is passed through a circular hole in which a ring, funnel, nozzle or slot is used, which creates a low-stress deformation in a way similar to sensory evaluation through human panels (Alley, 1980; Carrera-gallissà, Capdevila, & Valldeperas, 2014; Ciesielska-Wrobel & Van Langenhove, 2012; Grinevičiūtė & Gutauskas, 2004; Strazdiene, Martisiute, Gutauskas, & Papreckiene, 2003). It is said that this method is capable of simulating some hand modes such as drapability, stretch as surface friction as the fabrics get folded, sheared, bent, compressed, and rubbed against the inner wall of the ring/funnel/nozzle/slot during the extraction. Some notable extraction methods have been known or commercialized as Phabrometer® (Pan, 2007; Pan & Yen, 1992; Pan, Zeronian, & Ryu, 1993; Yim & Kan, 2014), Handle-o-meter (Abu-Rous, Liftinger, Innerlohinger, Malengier, & Vasile, 2017; Thwing-Albert Instrument Company, 2005), and El-Mogahzy-Kilinc method (El Mogahzy, Kilinc, & Hassan, 2005). There are also a number of methods reported in the literature, used by textile companies or in academic research where they normally capture only a single or limited spectrum of fabric properties to associate with some handle aspects especially on bending stiffness and friction (Dawes & Owen, 1971; Kocik et al., 2005; Peirce, 1930b; Sun et al., 2017). This is still a common practise in certain textile industries, for the main reason that the integrated system like KES-FB and SiroFAST are complex and more technically-savvy personnel are needed to analyse and interpret the data. Nevertheless, as no single fabric parameter can be able to solely represent the handle, the use of the methods is limited to only specified fabrics.

In the current decade, a new device called Fabric Touch Tester (FTT) has been commercialized by SDL Atlas (Liao et.al, 2014). This device is an output from the work of a group of researcher in The Hong Kong Polytechnic University. Contrary to KES-FB and FAST which have several devices integrated within a system, FTT, a stand-alone instrument that is claimed to measure several fabric properties and estimate comfort value through predictive models embedded in its software (Rycobel Group, 2019; SDL Atlas, 2014). The models are generated based on human assessment of various type of fabrics, but have never been disclosed by the manufacturer. Compared with the two prolific systems mentioned before, the measurement of thermal response is included in the FTT modules, apart from mechanical measurements i.e. bending, compression, surface friction and roughness. Hence, thermal and mechanical properties of the fabrics can be simultaneously measured under the same climatic condition (Hu et al., 2006). Thermal stimuli such as warmness and dampness have effect on the overall tactile comfort status of the wearer. It is also reported that thermal-wet comfort explained around 40% of the total comfort perception (Li, 2001). Therefore, merging the thermal-mechanical evaluation would give a better characterization of the tactile sensory properties for fabric-skin contact during wear. Quite recently, a new device named Material Tactile Tester (MTT) is introduced in a research led by Yao (Yao, Peng, & Yang, 2018). This device resembled the FTT as they used the same prediction model and classification method as FTT. However, it is developed as a mechanically improved version of the FTT especially in friction and compression module. As it is not yet commercially available in the market and no further research on it is reported, information on it is limited.

Newer fabric handle measurement devices also include Tissue Softness Analyzer (TSA) (Abu-Rous et al., 2017; Grüner, 2016) and Quick-Intelligent Handle Evaluation System for Fabrics (QIHES-F) (Sun, Zhang, Liu, & Du, 2018). TSA is mainly developed for tissue/nonwoven industry, based on the vibrations captured at different signal peaks that correspond to a certain hand feel i.e. smoothness-roughness and softness. QIHES-F is developed as a better version of a previously manufactured system named Comprehensive Handle Evaluation System for Fabrics and Yarns (CHES-FY) (Gao, Du, & Yu, 2013; Sun et al., 2017). It was an attempt from the researchers to build a simpler handle measurement system that can measure multiple properties including weight, bending, friction, tensile and compression behaviour of fabric through a single test. However, the device is still in prototype version, hence, as MTT, limited information and access to it is expected.

Besides the objective tools and subjective judgement by human panels described above, predictions models were developed to make estimation on the fabric handle or haptic perception based on some pool of objective or subjective data of the previously tested fabrics.

Every fabric handle measurement method has their own predictive models which was developed by their manufacturer or inventor through modelling methods. Several modelling methods found in the literature includes statistical, neural network, fuzzy logic and also biomechanical (Ciesielska-Wrobel, Langenhove, & Grabowska, 2014; El-Ghezal Jeguirim et al., 2011; Karthikeyan & Sztandera, 2010; Park, Hwang, Kang, & Yeo, 2000; Sztandera, 2009; Wong, Li, & Yeung, 2003, 2004). Figure 1-2 gives a visualization on the methods used for fabric handle assessment for tactile comfort.

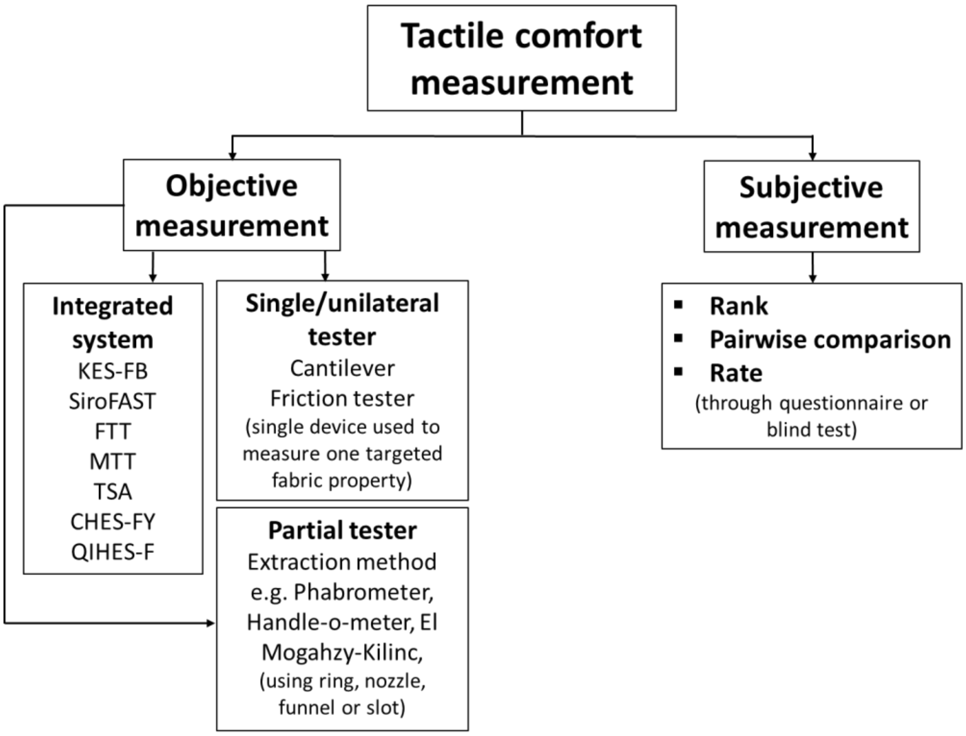

Figure 1-2 Summary list of tactile comfort measurement methods clustered into type category

1.3 Problem statements and research questions

Generally, a comfortable garment is often associated with having attributes of soft and smooth to touch, able to regulate moisture from body and surrounding area to give a pleasant cool-warm feel, non-prickly and also flexible or not stiff to some extent. Wearing garments which can satisfy our needs, be it physical, physiological and psychological gives a comfortable feeling to the wearer and to be in a state of comfort is always a need for every individual. It is an important aspect as being comfortable relates to a good quality of life. Hence, being comfortable in what we are wearing is one of the signs that shows a contentment in life, a way for a fulfilment of life. Research in textiles especially on comfort studies provide significant meaning to the human needs in a way that it can improve our quality of life.

However, the sensation we feel such as soft, smooth, stiff, rough, warm when in contact with the garments are terms that may give different interpretation to every individual. It is a subjective type of argument in which one might have the same pattern of sensation with the other or it could totally contrast. For instance, the same fabric could be perceived as smooth by someone, but as rough by someone else or even if both agree that the fabric is smooth, it could be that the degree of smoothness is different between the two evaluators. The terms used to describe the attributes of the fabrics seem to be imprecise, thus a comparison between fabrics is merely through one's perception which allows for different interpretation. Hence, to avoid the subjectivity in this matter and to enable to communicate about the fabrics attributes in the same language, **there is a need to measure the tactile behaviour of the fabrics in an objective manner.**

Since humans are the ones who generate the tactile feel variations on fabrics, they should not be interfered or involved in the objective tactile assessment. In other word, we want the machines to take-over our work to do the 'feel' evaluation as if we are taking our hands out of measuring handle of the fabrics. With this being said, instead of obtaining an un-scalable answer from humans, numerical values will be assigned by the machines. By having these values, the terms or attributes of the fabrics mentioned earlier are given an arithmetical identity so that we are now able to compare one fabric to another using the same language that can be understood by others.

Textile handle machines measure the physical and mechanical aspects of fabrics, and next using algorithm to predict the values of human touch. The obtained values from the machines should reflect the perceived feel of human. For that, at least two procedures are needed to enable this to happen; i) to convert human value of the fabrics into scalable or numerical form and ii) to train some sets of value obtained from humans and thus be able to generate an algorithm for hand prediction of fabrics of various types. There are a number of machines or devices developed for this purpose. The famous ones, Kawabata Evaluation System for Fabrics (KES-FB) (Kawabata & Niwa, 1989) and Fabric Assurance for Simple Testing (SiroFAST) (De Boos & Tester, 1994) are available in the market since 1980's. However, due to high in price and also technicality issues of the systems, some textile industries are still reluctant to use them, thus they developed their own way to assess the fabrics handle, albeit through human evaluation or simple available in-house devices. In the recent decade, Fabric Touch Tester (FTT) (Hu et al., 2006; Liao et al., 2014) seems to be the latest addition in the market. This single device claimed to measure fabric thermal-mechanical properties and predicts the comfort indices of the fabrics simultaneously for warp and weft less than five minutes per sample set.

Up till now, the way to perform the objective evaluation is still open. Hence, to begin with, FTT is taken as the focus in this study as it is the latest device introduced to the mass community. There is a huge possibility on how this device could be improved. Therefore, this device needs to be thoroughly examined, first by focusing on its predictive comfort models as well as single indices measurement. **The reliability of the device to carry out the handle measurement must be confirmed and the validity of the models should be tested with various types of fabrics and to be backed-up with the results from human assessment.**

As the human assessment serves as the basis for the development of comfort models for FTT and also other devices, the importance for having a non-bias human evaluation for not only various but a large number of fabrics is much needed. This is because, the more varieties of the fabrics used in the human assessment, the better the algorithm that can be developed for handle prediction. However, assessing a lot of fabrics might stress out the assessors, in addition to lengthy procedures which takes much time, and potentially jeopardize the judgement of the human panels. **Knowing the importance of human assessment on fabric handle to provide data to be used in objective measurement tools, a comprehensive approach to assess the handle of a high number of fabrics, particularly to deter the human error factors which are caused by fatigue and loss of concentration, is required.**

The research also needs to examine the state-of-the-art approach on fabric handle or haptic modelling as a way forward to enable a deeper understanding of the current state of the field. An insight looks of the methods and also the advantages and drawbacks of the models may give important notes to the development of the upcoming models.

1.4 Aims and objectives of the study

This study aims **to evaluate human tactile response to haptic sensations on clothing fabrics through analysis on subjective and objective measurement of fabric handle.** As the comfort itself is a very nebulous term and it is too broad to be covered, the focus is only on the **tactile perspective**, as it is the prominent sensation of comfort perception, in comparison with other factors i.e. visual, auditory and olfactory.

The key objective of this research work is to **determine the suitability and reliability** of the latest objective measurement tool, i.e. FTT to measure fabric handle. The work extends to **investigate the approach on human assessment** of fabric handle and **suggest improvement on the methods.** Furthermore, **the comfort models from various methods e.g. statistical, neural network and fuzzy logic, are to be analysed and discussed.**

1.5 Thesis outline

This thesis consists of six chapters.

In this Chapter 1, an overview and general introduction on the topic was provided. The broad definition of comfort was presented; branches of comfort studies were also discussed, thus lead to the main topic on tactile comfort and the measurements. The aim and objectives were also identified as well as the flow of the studies as mentioned here.

In Chapter 2, the objective measurement of the fabric handle is described. FTT is employed as the device under focus in this study as it is a relatively newly commercialized device to quantify the fabric handle. The data on fabric handle obtained from this device is analysed in order to assess the reliability and feasibility of it.

Chapter 3 is about the human assessment of the fabric hand in which the current available methods and limitation in the assessment procedures are discussed. Due to the limitation in subjective method to cater the high number of samples, a set of an improved protocols is suggested regarding the human handle evaluation of large sample set of fabrics.

In Chapter 4, predictive models of fabric handle from previous studies are presented. The advantages and drawbacks of the models are analysed and discussed. An improved idea on a biomechanical model is also presented.

The combination results of human assessments and objective methods are discussed in Chapter 5. Detail analysis is presented on the statistical models generated from the experiments.

Lastly, in Chapter 6, based on the findings on the studies, a conclusive note is presented which also summarise the key results of the thesis.

Figure 1-3 visualizes the division of chapters in this thesis.

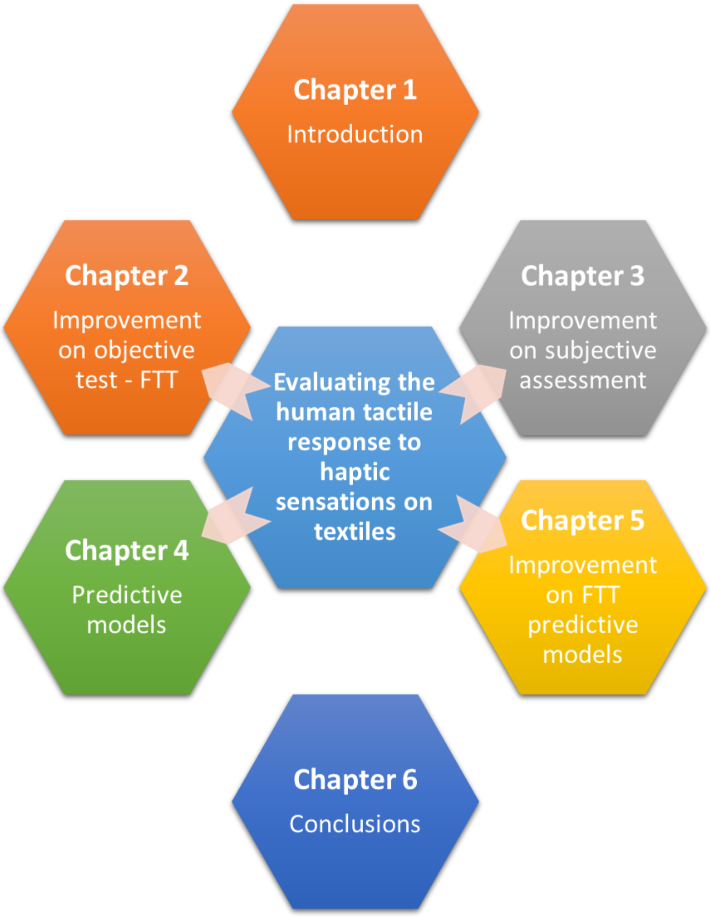

Figure 1-3 Overview of the thesis

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2

Fabric Touch Tester – mechanism and analysis on single index

Science is not only a disciple of reason
but, also, one of romance and passion.

Stephen Hawking

This chapter presents the information of the FTT which comprises the introduction on the device itself including the modules and reconstruction of the predictive comfort models, literatures, some practical aspects to handle the device, and also the author's attempts to check the compatibility of a singular index of FTT in comparison with common methods.

This chapter is partially based on the publications:

Binti Haji Musa, A., Malengier, B., Vasile, S., & Van Langenhove, L. (2017). Practical considerations of the FTT device for fabric comfort evaluation. Journal of Fashion Technology & Textile Engineering, S4-003, 1–4.

Binti Haji Musa, A., Malengier, B., Vasile, S., Van Langenhove, L., & De Raeve, A. (2018). Analysis and comparison of thickness and bending measurements from fabric touch tester (FTT) and standard methods. Autex Research Journal, 18(1), 51–60.

2.1 Introduction

Fabric Touch Tester (FTT) device was relatively recently manufactured by SDL Atlas as a commercialized output from researches led by Prof Yi Li at The Hong Kong Polytechnic University. The current model of FTT was first mentioned in a research paper in 2014 (Liao et al., 2014). However, the idea of having a single integrated device for fabric handle assessment had started earlier. The same research group introduced the laboratory prototype version in 2006 as reported in a paper (Hu et al., 2006) and also included in the doctoral thesis of the first author (Hu, 2006). However, the prototype version had several differences in the testing mechanism especially in the fabric surface measurement. FTT measures concurrently 13 fabric indices related to tactile properties, and predict three comfort indices i.e. smoothness, softness and warmth, and also global indices total touch and total hand. Despite the vast methods and devices available today, FTT is developed to bring a better alternative to the field after considering and understanding the findings of neuroscience studies in regards to touch feels.

The neuroscience theory on touch perception states that there are four types of touch stimuli i.e. thermal, cutaneous, proprioceptive and irritant or pain stimulus which are detected by the nerve receptors. Thermal stimulus denotes the relative high-low temperature of the object touched, cutaneous stimulus relates to shape and texture properties, proprioceptive stimulus is regarding the position and motion, and irritant or pain stimulus is about anything that induces skin irritation e.g. prickling or itch-like sensation. To sum up the information, in the context of physical measurement of fabric feel, thermal, texture and deformation properties of a fabric should be considered. Furthermore, the interaction between these stimuli would affect the overall touch perception as well. For example, some studies reported that temperature could influence the neural response of tactile stimuli (Ho, Watanabe, Ando, & Kashino, 2011; Li & Wong, 2006; Liao et al., 2016). It means that the sensitivity of other tactile receptors could be affected by thermal stimulus. Therefore, other than physical measurement such as bending, compression and friction, thermal should be included as part of tactile evaluation, and the measurement of all the properties should be made simultaneously as to account for the interaction between the stimuli.

There measurement made by the key fabric handle systems, KES-FB and SiroFAST exclude the thermal evaluation in their modules. Other than the price that is relatively high, the lengthy testing procedures and complexity in interpreting the results make them less attractive to the stakeholders. These systems also do not support a simultaneous measurement of the handle properties and hence the influence from the interaction between them are neglected. Therefore, FTT was developed to tackle parts of the loopholes made by the previous inventions. The main advantages of the device are listed below;

i. FTT provides a simultaneous measurement of fabric handle which consist of compression, bending, surface and thermal properties,
ii. FTT constitutes of only a single device and the measurement is fast i.e. less than five minutes overall for a set of samples (two pieces) including warp and weft, and also outside (technical face or face) and inside (technical back or back or skin touching side),

iii. FTT fabric indices relate to the physical meaning, hence the interpretation of the results is much easier to the laymen language.

After several years in the market, there is still limited work pertaining to the use of this device. In 2013, an exploratory investigation on FTT softness-stiffness sensation is reported by the same group of researchers in The Hong Kong Polytechnic University (Wu et al., 2013). The researchers conclude that stiffness can be objectively measured by FTT and significant correlations were found with subjective assessment and KES-FB. In the following year, Liao et al. reported the refinement of the FTT from the previous laboratory version (Liao et al., 2014). They investigated the effects of thermal perceptions on the tactile perceptions and found correlations between FTT results and subjective evaluation scores. A study by the same team about psychophysical relations between various conditions of fabric thermal-tactile properties and psychological touch perceptions utilized the FTT device to obtain physical data. The results imply that both thermal and tactile physical stimuli affect the touch sensation simultaneously (Liao et al., 2016).

A project financed by the European Commission named '*Touché: Boosting innovation through application of basic understanding of the process and testing of textile touch and fabric feel'* (Touché, 2015) employed this device to study variation of fabric hand with various production settings, fibre type and fabric treatments among others. It was reported that FTT seems to be sensitive enough to discriminate between fabrics for protective clothing with comparable mass per surface area or thickness (Vasile et al., 2016). Moreover, the device could successfully distinguish between tactile properties of cellulosic (e.g. lyocell, modal, etc.) fabrics and the predicted FTT comfort indices (e.g. softness, smoothness) were in good agreements with the expert panels and Tissue Softness Analyzer (TSA) (Abu-Rous, 2016). This thesis is partially an output from the project. The author of this thesis also published her work together with her co-researchers on the reliability of the device thickness and bending measurement in comparison with the standard method and they found good correlations between both methods (Binti Haji Musa et al., 2018). Another paper by the same team describes several guidelines and practical considerations on using the FTT which was written based on the authors' own experiences and observation in handling the device (Binti Haji Musa, Malengier, Vasile, & Van Langenhove, 2018b). The excerpt of the research papers will also be included in this thesis in a later section.

Research comparing several types of objective measurement tools i.e. FTT, TSA, Phabrometer®, and also human assessment observed a wide agreement among the physical methods in the extreme ranges of fabric handle. However, high deviations obtained for the middle range due to similarity of fabrics tested (Abu-Rous et al., 2017; Abu-Rous, Malengier, Liftinger, & Innerlohinger, 2018). The use of FTT is further reported particularly on its ability to discriminate the comfort indices of knitted fabrics differentiated by finishing treatments (Vasile, Malengier, De Raeve, & Binti Haji Musa, 2017a). The device was also used to measure the handle of mattress ticking fabrics with variations in production parameter setting i.e. mass per unit area, softener concentration and percentage of viscose composition (Vasile, Malengier, Deruyck, & De Raeve, 2019). The researchers found strong correlations between the FTT fabric indices and tactile properties assessed by the panels, except warmth, which suggests that the FTT is suitable to assess mattress ticking fabrics with elevated mass per unit area and uneven texture. As the texture and usage of mattress ticking fabrics are different from the common clothing fabrics from which the FTT models are constructed, they generated explicit models that match the handle perception of that specified type of fabrics. Another study using mattress fabrics treated with flame retardant finish also agree that FTT is capable to assess the variation in these types of fabric (Binti Haji Musa, Malengier, Vasile, & Van Langenhove, 2018a). However, the performance of the predictive comfort models of FTT was not included. FTT was reported to be able to discern the fabrics shown by the variations of the fabric indices. However, the competency of the comfort indices is not thoroughly discussed in the literature.

To the best of the author's knowledge, studies on the FTT are only found from its pioneering research institution i.e. The Hong Kong Polytechnic University, and another one is from a consortium of different institutions through a funded project by European Commission (Touché, 2015). No standard yet exists for the measurement using the FTT; thus, the handling methods are just based on the manufacturer's manual guidelines. Despite the advantages listed earlier, a cross-check needs to be made to confirm the reliability and capability of the device to be used in this field of study. Hence, some comparisons on the fabric index of measurement in FTT with other devices are included in this chapter, and the studies on the predictive models expressed by the comfort indices will be presented in a later chapter.

2.2 Measurement principle of FTT

FTT comprises of four modules i.e. compression, thermal, bending and surface. These modules are simultaneously run during the test. The device requires samples to be in an L-shape as to match the mechanical design of it, specified by the machine manufacturer (SDL Atlas, 2014). The dimension of the sample is shown in Figure 2-1. With this shape, the square centre part is placed horizontally on the bottom or lower plate which accounts for the thermal and compression measurement, and the two arms of the L-shape are on the adjacent platforms to perform bending and surface evaluation. The design of the two platforms enables the warp/wale and weft/course directions of a sample to be tested concurrently, thus save time. The two platforms have replicate sets of bending and surface measurement components. A set of two L samples is needed, one for outside and one for inside to complete the measurement for a type of fabric consisting of warp and weft, outside and inside, and takes less than five minutes to finish. Two samples are needed as turning the sample around is not accurate as the sample was heated and compressed.

Prior to testing, the top or upper plate is controlled at 10°C higher than the bottom plate as to mimic the temperature difference between skin and textiles. The top plate which consist of a thermal sensor is made to descend and touches the fabric on the bottom plate. Together with the bottom plate making the sample sandwiched between them, the sample is brought further downward by both plates and after several seconds, they reach the lowest position and then go back to their initial position. The dynamic responses of the sample are recorded along the test period with total of 13 fabric indices defined. Based on that, FTT software will make calculations for the predictions of three comfort indices i.e. smoothness, softness and warmth, and two global indices i.e. total hand and total touch. These indices will be further elaborated in the subsequent sections. Figure 2-2 shows the FTT device used in this research work. The FTT test should be done in a standard atmosphere for testing. Also, prior testing, all samples must be conditioned for at least 24 hours in a conditioning room, controlled at 21°C ± 2°C and relative humidity of 65% ± 4% (ASTM International, 2004). A standard yellow fabric is chosen by the manufacturer to be used as a reference material for calibration purpose. The fabric is a double-knit jacquard with polyester and polyurethane blends. The sensors functionality can also be checked through the self-check button included in the system.

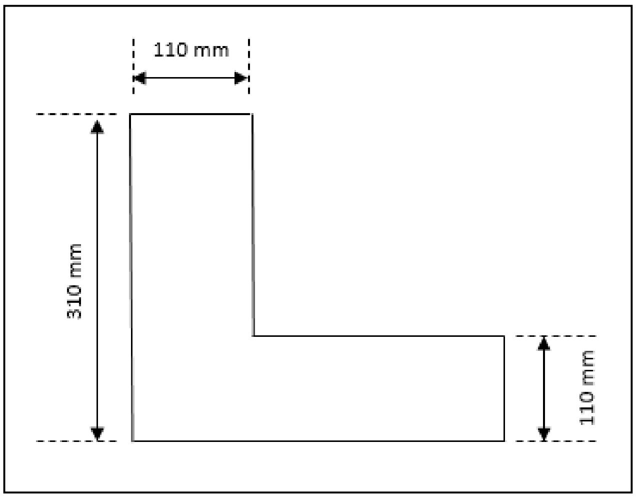

Figure 2-1 Fabric sample dimension

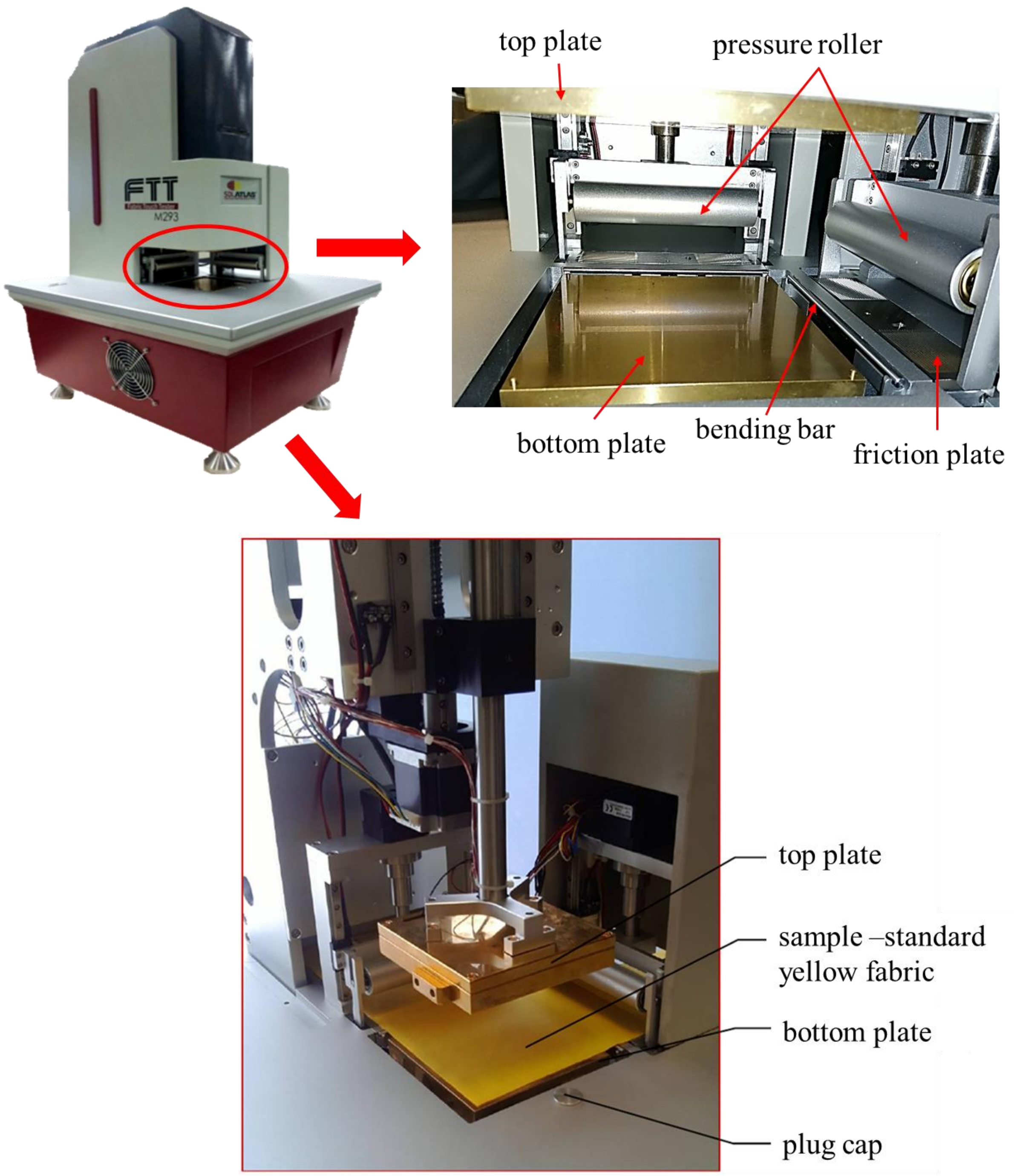

Figure 2-2 Fabric touch tester device with several highlighted components

2.3 FTT modules and fabric indices

The four modules of FTT, i.e. compression, bending, thermal and surface are activated simultaneously to measure a total of 13 indices of which some of them i.e. bending and surface, are differentiated by warp and weft directions, and for the others i.e. compression and thermal, only global measurements are involved. In the system software, normally a small letter 'a' and 'e' is added following the abbreviation of the indices to note the differences between the measurement in warp or wale ('a') and weft or course ('e'). For example, SFCa refers to measurement of Surface Friction Coefficient in warp or wale direction, and SFCe is that of weft or course. In addition to that, sometimes, a small letter ‘m’ is added to describe a combination of warp/wale and weft/course measurement, but that is only for a computed value from the indices which has run through some statistical analysis procedures. The whole list of the 13 indices and their interpretations is given is Table 2-1. Figure 2-3 shows the system main interface of the FTT when it is in running mode.

Table 2-1 Interpretation of the FTT fabric indices

Item	**Fabric Property**	**Index**	**Description**	**Unit given by FTT software**	**SI unit**	**Usual interpretations**
1	Bending	BAR	Bending Average Rigidity	gf mm rad^{-1}	N m rad^{-1}	Force needed to bend per radian
2		BW	Bending Work	gf mm rad	N m rad	Work needed to bend
3	Surface-friction	SFC	Surface Friction Coefficient	-	-	Friction coefficient on surface with ribbed plate
4	Surface-roughness	SRA	Surface Rough-ness Amplitude	μ m	m	Roughness irregular wave amplitude
5		SRW	Surface Rough-ness Wavelength	mm	m	Roughness irregular wave wavelength
6	Compression	CW	Compression Work	gf mm	N m	Work needed to compress the specimen
7		CRR	Compression Recovery Rate	-	-	Percentage of thickness changes after compressed
8		CAR	Compression Average Rigidity	gf cm^{-2} mm^{-1}	N m^{-3}	Forces needed to compress per mm
9		RAR	Recovery Average Rigidity	gf cm^{-2} mm^{-1}	N m^{-3}	Forces reflected when recovery per mm
10		T	Thickness	mm	m	Thickness of the materials
11	Thermal conductivity	TCC	Thermal Conductivity under Compression	10^{-3} W m^{-1} °C^{-1}	W m^{-1} °C^{-1}	Energy transmitted per degree per m per second under specimen compression
12		TCR	Thermal Conductivity under Recovery	10^{-3} W m^{-1} °C^{-1}	W m^{-1} °C^{-1}	Energy transmitted per degree per m per second under specimen recovery
13		Qmax	Thermal Maximum Flux	W m^{-2}	W m^{-2}	Maximum energy trans-mitted during compression

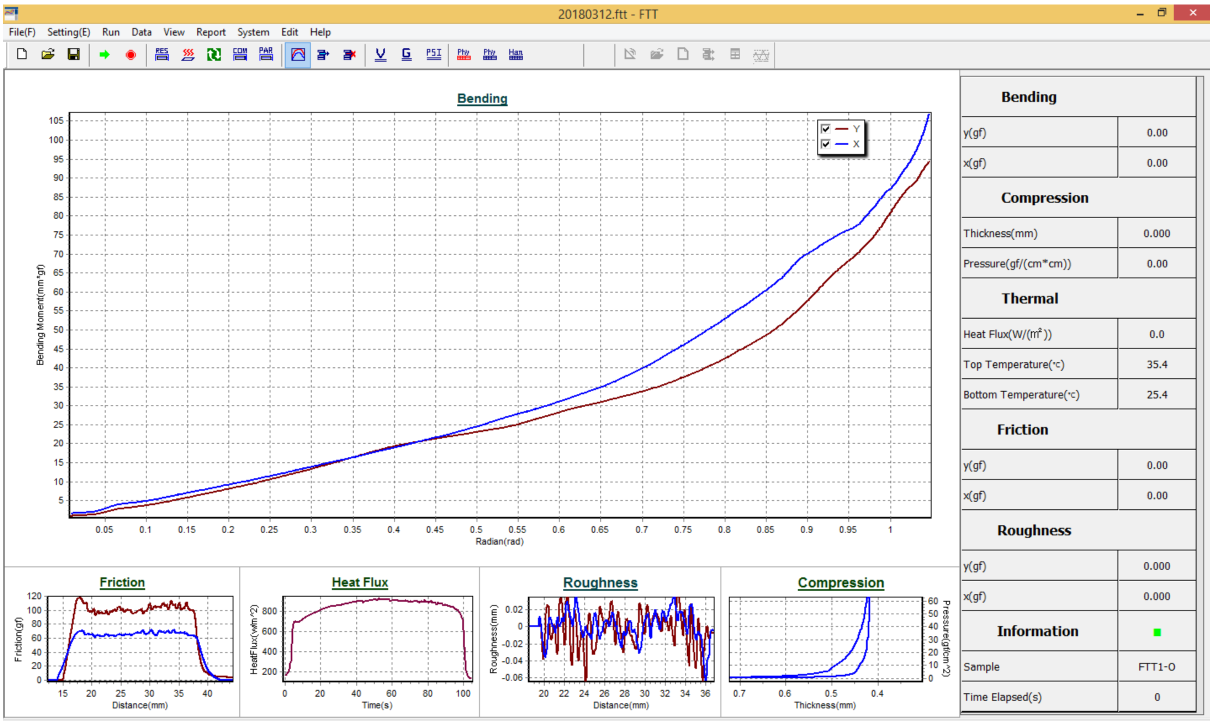

Figure 2-3 FTT main interface during the test

2.3.1 Compression module

The compression module in FTT reflects the act of finger pressing or squeezing on fabrics. During the pressing, the sample is compressed by the force provided by the finger. The compression module mainly consists of two plates i.e. top/upper and bottom/lower, force sensors and a laser distance sensor. During the measurement, the upper plate will be moved downward by a traction device, applying a continuously increasing normal force from 0 to 8470 gf (i.e. 0-70 gf/cm^2). The force sensors which are connected to the bottom plate will record the dynamic force and the laser distance sensor will record the distance of the two plates. Compression forces are converted to pressure (unit – gf/mm^2) and the distance between the plates is measured (unit – mm). Figure 2-4 visualizes the compression modules and a typical pressure P(z) versus thickness curve z, as well as the recovery curve $P_r(z)$ are illustrated in Figure 2-5.

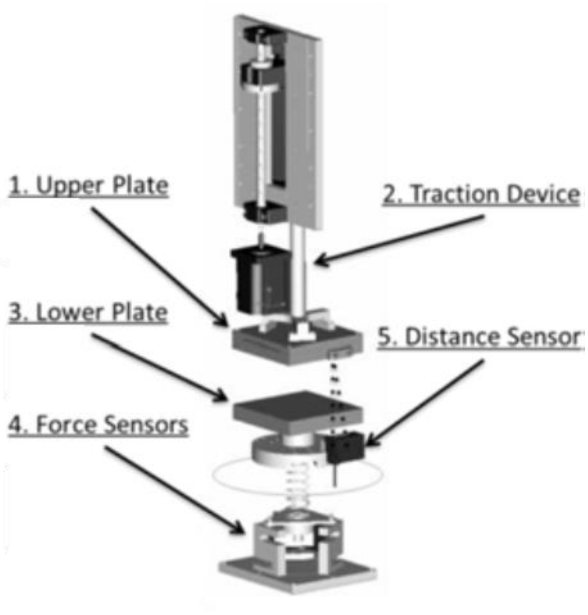

Figure 2-4 Mechanical design of FTT compression module (Liao et al., 2014)

From the compression module, five indices are defined, including thickness, abbreviated as T, which is the distance measured at 41 gf/cm^2. Others are Compression Work (CW), Compression Recovery Rate (CRR), Compression Average Rigidity (CAR) and Recovery Average Rigidity (RAR). The indices are defined as follows;

$$CW = \int_{D_a}^{D_c} P(z)\, dz\,,$$

$$CRR = \frac{\int_{D_c}^{D_a} P_r(z)\, dz}{\int_{D_a}^{D_c} P(z)\, dz}\,,$$

$$CAR = \frac{P_i - P_j}{D_j - D_i}\,,$$

$$RAR = \frac{P_i - P_j}{D_m - D_n}$$

For CW, D_a is the measurement of thickness at zero pressure or in practical, when the thickness starts rising, and D_c at maximum pressure which is at 70 gf/cm^2. CRR is the ratio of recovery work to compression work. CAR and RAR are the measurement of average force needed to compress 1 mm of sample, considering the middle 60% of compression and recovery process, respectively. P_i and P_j are the 20% and 80% pressure level, D_i and D_j are the thickness in compression, D_m and D_n in recovery, at those pressure levels.

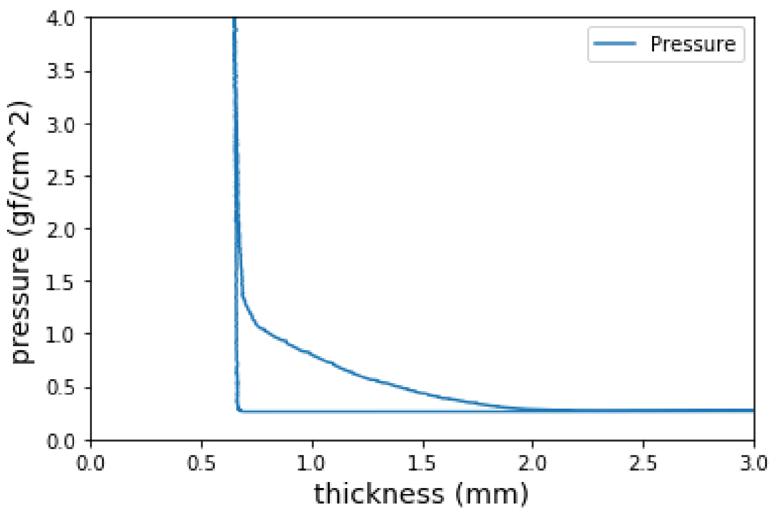

Figure 2-5 A typical pressure versus thickness curve constructed from the FTT full data

2.3.2 Thermal module

The temperature difference between human skin and fabrics gives coolness-warmness feel. The body is normally 10°C higher from the fabrics, hence heat is transferred between these two mediums. In FTT, the upper plate is heated at 10°C higher than the lower plate to mimic this phenomenon. As soon as the skin touch the fabric, heat flux begins. FTT thermal module consists of a heat flux sensor which is placed at the centre of the upper plate to record the continuous heat flux through the fabrics during the compression process. A heat flux versus thickness curve (H(z), and H_r(z) for recovery) is generated (see Figure 2-6) and three indices are defined within this module, i.e. Thermal Conductivity when Compression and Recovery (TCC and TCR respectively), also Qmax which is the maximum heat flux measured that is observed at the initial fabric-skin contact and relates to the immediate cool-warm feeling. TCC and TCR are given as follows;

$$TCC = \frac{H(D_i)D_i}{C}, and\ TCR = \frac{H_r(D_j)\,D_j}{C}$$

Here, C is the temperature difference between the upper and lower plates i.e. 10°C, D_i and D_j are the thickness of the sample under 41 gf/cm^2 (0.41 Newton/cm^2) pressure during compression and recovery, respectively. H(D_i) and H(D_j) are the heat flux measured at the time D_i and D_j are obtained.

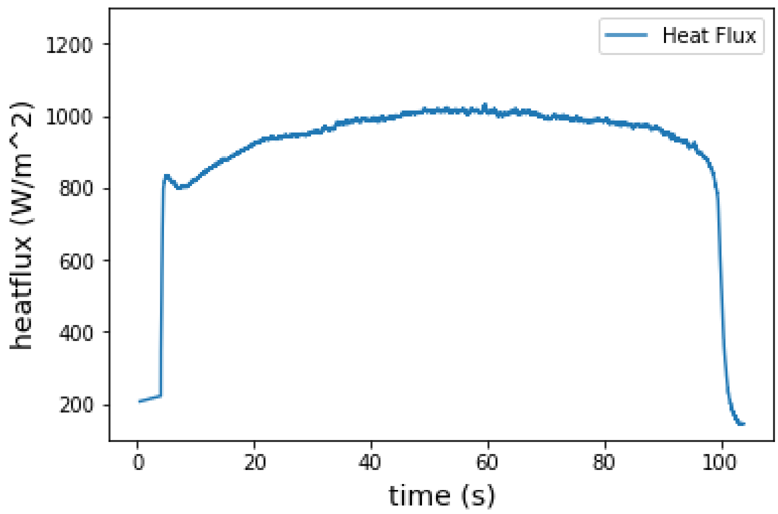

Figure 2-6 A typical heat flux versus time curve constructed from the FTT full data

2.3.3 Bending module

The act of pinching a fabric is like imposing force onto it which is usually done with two fingers. The fabric is bent by this act and thus provides information especially on stiffness of the material. Bending module in FTT simulates this action incorporating the use of bending bars which are located on the same level as the bottom plate. The plate is then moved downwards, together with the centre part of the sample making a bend with a different height of the plate and the bending bars located at the adjacent arms (see Figure 2-7). The bar is pushed downwards to apply the bending force and force sensors are incorporated to record the exerted force during the test. As the plate moves down, an angle is obtained over the bending bar. The recorded bending force is converted into bending moment and the angle is given in radian. A bending moment versus bending angle curve, M(a) is generated for the measurement (see Figure 2-8 and Figure 2-9). From the curve, two indices are established under bending module, i.e. Bending Work (BW) and Bending Average Rigidity (BAR), as given below;

$$BW = \int_{1}^{B} M(a)da,$$

$$BAR = \frac{M(R_D) - M(R_C)}{R_D - R_C}$$

BW is the total work done on the sample, that is calculated by the integral of the curve. For BAR, it is defined as the average moment needed to bend 1 radian of sample during the middle 60% of the bending process. Hence, R_D to R_C are the angle values at 20% and 80% of maximum bending moment, and $M(R_D)$ and $M(R_C)$ are the bending moment recorded there.

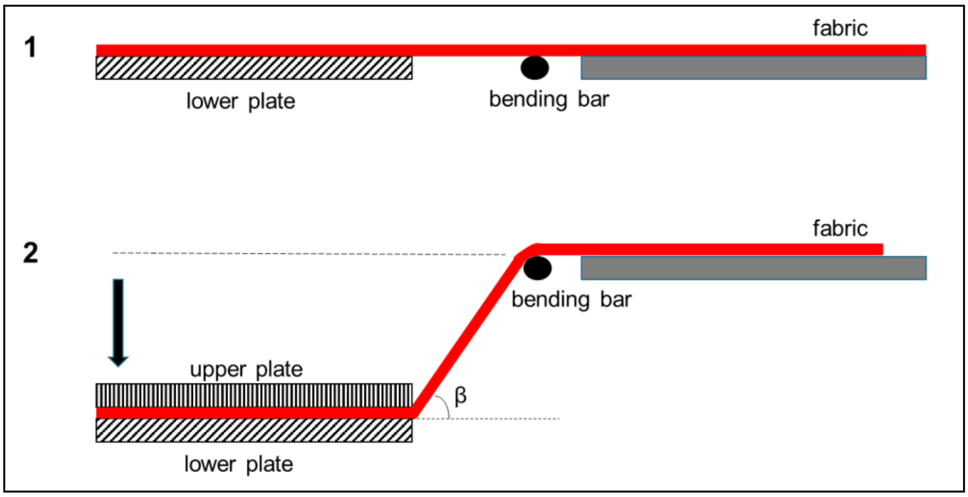

Figure 2-7 Schematic diagram of bending motion in FTT

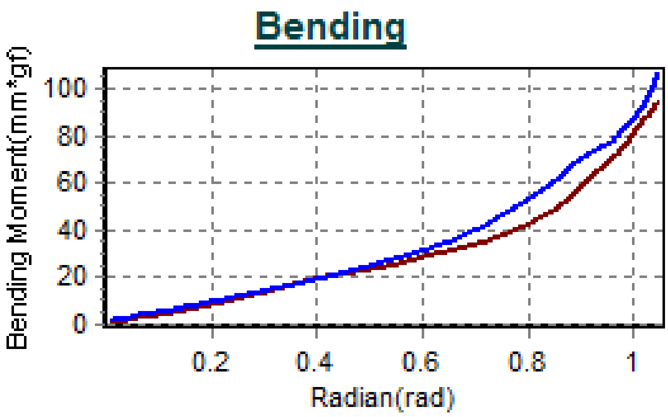

Figure 2-8 A typical bending moment versus radian curve from the FTT system interface

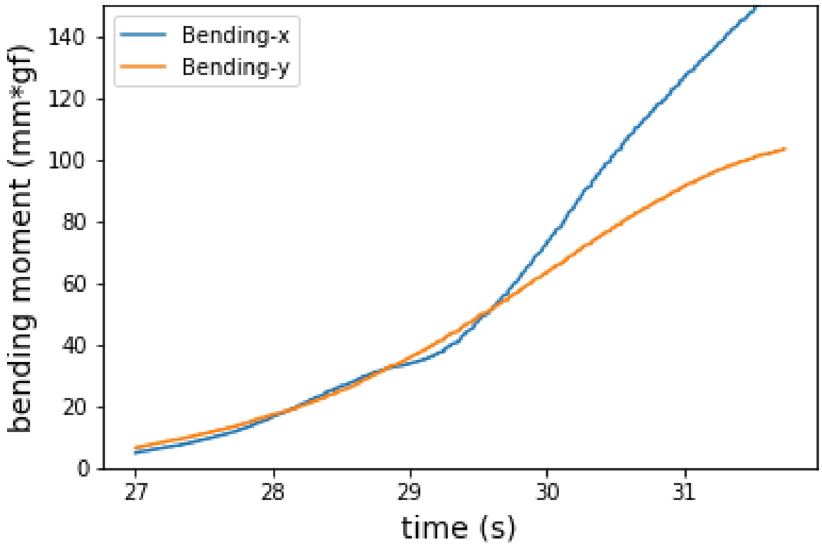

Figure 2-9 A typical bending moment versus time curve constructed from the FTT full data (the time here would reflect the bending angle during the measurement)

2.3.4 Surface module

When the finger moves across the fabric surface, information is gathered e.g. the texture and smoothness feels. The surface module of FTT captures the surface information through friction and roughness measurements. For friction, the dynamic coefficient of friction is obtained by incorporating a metal friction plate which has a ribbed surface, a force sensor and a pressure roller. During the test, the sample will move onto the friction plate, thus the plate will push the force sensor that is placed underneath. A normal force of 140±5 gf is provided by the pressure roller which is placed on top of the sample, next to the friction plate. A common frictional force versus distance curve (see Figure 2-10) is generated to quantify the dynamic coefficient of friction or known as SFC or Surface Friction Coefficient index in FTT. SFC is obtained by dividing the average value of the measured kinetic friction forces (F) by the given normal force (N), i.e. 140±5 gf, with a and b denote the start and end of kinetic friction movement, respectively.

$$SFC = \frac{F}{N} = \frac{1}{N(b-a)}\int_a^b F dx,$$

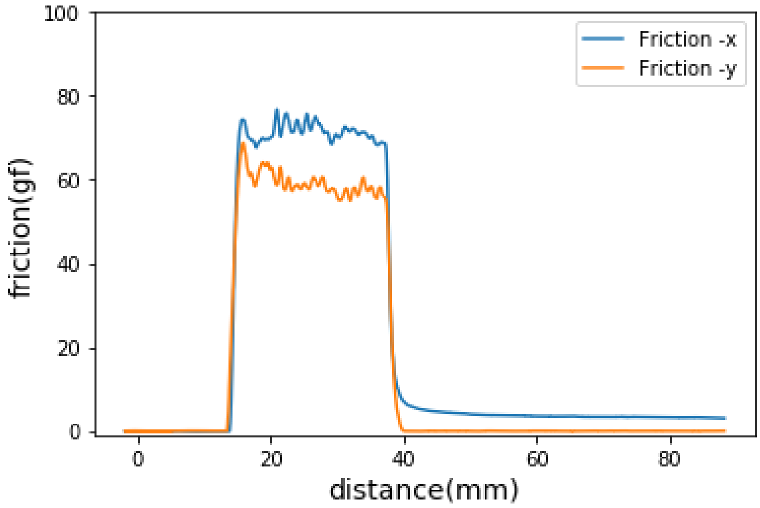

Figure 2-10 A typical frictional force versus distance curve constructed from the FTT full data

Roughness property is related to geometrical variances of a sample surface. In FTT, it is quantified through a movement of a pin-shaped detector when a sample is passed over it. The movement made by the pin is measured by a laser sensor, such as the one used in the compression module. Based on the pin movement, a wavy curve is expected for the measurement (see Figure 2-11-left). A line for the average roughness height, peak and trough values for the curve are defined. Peak and trough correspond to the maximum and minimum value of the wave for every three intersections of the measured curve and average line. Two indices are established for the roughness measurement i.e. Surface Roughness Amplitude (SRA) and Surface Roughness Wavelength (SRW), which are extracted from the measured profile. SRA is the average difference between the peak and trough values of the roughness wave. SRW is the average moving distance for every three intersections points of the average line with the measured line. The indices are defined as below;

$$SRA = \overleftarrow{R_p} - \overleftarrow{R_t} = \frac{1}{b}\sum_{x=1}^{b} R_{px} - \frac{1}{b}\sum_{x=1}^{b} R_{tx}$$

$$SRW = \frac{1}{M}\sum_{x=1}^{M} \left|X_{pn} - X_{tn}\right|$$

R_{px} and R_{tx} are the measured peak and trough value of the roughness wave when the sample moves at distance x, and b is the amount of peaks and trough recorded during the measurement. X_{pn} and X_{tn} are distances between an upward peak at average thickness and M is the total counts of groups of three successive intersections. Figure 2-11-right gives a visualization on the curve for the measurement of the indices.

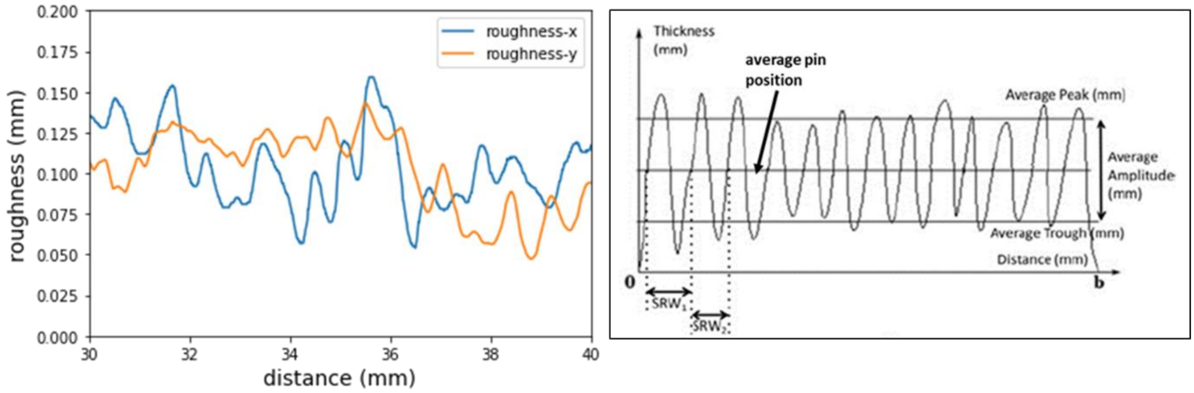

Figure 2-11 Roughness measurement with FTT; left- A typical roughness (thickness) versus distance curve constructed from the FTT full data, right- calculation diagram for SRA and SRW indices (Liao et al., 2014)

The specification of the FTT and its sensors are given in Table 2-2 below;

Table 2-2 FTT specification and technical details

No.	Item	Description	Specification
1	top plate	size L x W	120mm x 120mm
		weight	3075g
		maximum displacement	120mm
		moving down speed	1mm/s
		material	metal brass
2	bottom plate	size L x W	120mm x 120mm
		weight	2560g
		maximum distance	50.55mm
		material	metal brass
3	maximum pressure	pressure for end point	70gf/cm²

4	standard pressure	thickness measurement standard pressure	41gf/cm²
5	compression rate	fabric thickness per pound/inch² pressure	0-10.0mm/((0-1.0pound)/inch²)
6	temperature difference	temp.(top-plate) – temp. (bottom-plate) = 10ºC	+/- 0.1ºC
7	sample size	longitude and latitude	310mm*310mm L-shaped, width=110mm
8	sample thickness	maximum sample thickness	5.0mm / normal mode 20mm / compression mode
9	power supply	-	230/110V 50/60Hz 5A
10	external size	L x W x H	510 x 600 x 840 mm
11	gross weight	-	85kg
12	heat flux sensor	thin-film heat flux sensors	HFS-4 OMEGA
		max recorded thermal nominal	30,000 Btu/ ft²hr
		thermal resistance	0.01 ºf per Btu/ ft²hr
		accuracy	0.5% (% F.S.)
13	bending and friction sensor	sensors for bending& friction testing	LSB200
		capacity	250g
		output sensitivity	2.0± 0.1mv/v
		accuracy	0.05% (% F.S.)
14	load-bearing	pressure sensor	STC-10KG
		standard capacity	10kg x 3
		non repeatability	0.01% at 350+/-3 ohm
15	displacement	non-contact laser displacement sensor	KEYENCE
		model	IL-030
		measurements range	30mm
		non-linearity	±0.1%(F.S.=±5 mm, 25 - 35 mm)
		repeatability accuracy	2 μm
16	temperature	temperature sensor model	pt100
		thermal range	0-100ºC
17	location of lower test plate	distance of left side to working platform	10±0.2mm
		distance of frontal side to working platform	10±0.2mm
18	location of the friction plate	relative height difference to touch plate	0～0.2mm

19	location of the bending rod	distance of bending rod's axis to side of lower test plate	12±0.5mm
		relative height difference to upper surface of lower test plate	0～0.5mm
20	press roller	the weight of press roller	140±3g

2.4 FTT comfort indices

Based on the 13 indices measured, three comfort indices are predicted i.e. smoothness, softness and warmth. These three indices are chosen as the primary hand index and the total index value is called as total hand and total touch in FTT, which are also generated as the overall tactile comfort perception for the tested fabric. A number of fabrics particularly used for clothing, was assessed by human panels and the results served as inputs for the development of the models. However, the models are undisclosed by the manufacturer.

In FTT, the terms 'hand' and 'touch' are distinguished to give different connotation, although the use of these terms are commonly interchangeable in other occasions. 'Hand' is used to refer an active touch that is made consciously particularly by the skin on palm and fingers to evaluate the handle properties of the fabrics, whereas 'touch' is the opposite action in which passive evaluation of fabrics are made during wear normally by other parts of skin. Since the hands are moved to obtain information relating to the fabrics, hence the touch is active in the case of handling the fabrics (Ciesielska-Wrobel & Van Langenhove, 2012; Heller & Schiff, 1991; Li, 2001). Therefore, in this work, as measurements are consciously made on fabrics, active touch will be the main focus.

2.4.1 Reconstruction of FTT comfort indices

As the default comfort models of FTT are only known by the manufacturer, the models are reconstructed in order to understand how the they were derived. It is actually a reverse process of obtaining data in FTT. This is constructed based on a large FTT results database of more than 3,000 FTT runs, on a wide range of fabrics (i.e., clothing, terry, mattress ticking, fabrics with different treatments such as softeners, flame retardants etc.), and thus the models used internally by the FTT device to compute the results are retrieved. This should give an insight in the terms or indices constituted in the models, hence further analysis can be made for comparisons with the results of specified type of fabrics.

The models are regenerated by utilizing the python Statsmodels package. Only linear models were developed which only consider linear terms. For that, the ordinary least squares (OLS) combined with a stepwise regression was employed based on adjusted R^2. Terms i.e., FTT indices, were added as long as the adjusted R^2 of the model increases. At the same time, the relevance of the obtained coefficients was observed as terms were added. For that, the p-value for the t-statistics needed to be below 0.05 for the terms to be retained. This allows to construct an optimal model as only the most influenced terms with highly significant contribution are included in the reconstructed comfort models. Table 2-3 shows the results of the reconstructed models created.

Table 2-3 Reconstructed models of FTT reproduced from a database of more than 3000 runs of FTT experiments

Active		
Smoothness	**Softness**	**Warmth**
Full model Adj. R^2 = 1.000 Smoothness ~ CAR + BWa + TCR + CW + T + SRWa + Qmax + SFCe + BARa + SRWe + SFCa + BWe + BARe + TCC Intercept 7.682e-01 CAR 1.805e-04 BWa -7.250e-05 TCR -2.537e-12 CW 2.526e-04 T -8.400e-01 SRWa 1.161e-02 Qmax -3.553e-04 SFCe -2.646e-01 BARa 2.618e-04 SRWe 1.161e-02 SFCa -2.646e-01 BWe -7.250e-05 BARe 2.618e-04 TCC 7.000e-03	**Full model** Adj. R^2 = 1.000 Softness ~ BWe + CW + CAR + BWa + SRAe + TCC + SRWe + SRAa + SRWa Intercept 5.005e-01 BWe -2.290e-04 CW 1.980e-04 CAR 7.500e-05 BWa -2.290e-04 SRAe -4.920e-04 TCC 1.959e-03 SRWe 1.250e-02 SRAa -4.920e-04 SRWa 1.250e-02	**Full model** Adj. R^2 = 1.000 Warmth ~ CAR + T + CW + TCC + CRR + SRAa + SFCe + SRAe + SFCa Intercept 7.923e-01 CAR -1.570e-04 T 1.508e-01 CW 2.700e-05 TCC -1.719e-03 CRR -8.215e-02 SRAa 1.180e-04 SFCe -3.556e-02 SRAe 1.180e-04 SFCa -3.556e-02
Reduced model Adj. R^2 = 0.927 Smoothness ~ CAR + BWa + TCR + CW + T + SRWa Intercept 0.426 CAR 1.530e-04 BWa -6.000e-05 TCR 2.622e-03 CW 2.360e-04 T -6.694e-01 SRWa 1.325e-02	**Reduced model** Adj. R^2 = 0.968 Softness ~ BWe + CW + CAR + BWa Intercept 6.064e-01 BWe -2.460e-04 CW 1.810e-04 CAR 6.800e-05 BWa -2.130e-04	**Reduced model** Adj. R^2 = 0.983 Warmth ~ CAR + T Intercept 6.609e-01 CAR -1.630e-04 T 1.668e-01
Passive		
Smoothness	**Softness**	**Warmth**
Full model Adj. R^2 = 1.000 Smoothness ~ T + BWa + CAR + BWe + SRWe + SRWa + CW + TCR + Qmax + TCC Intercept 7.812e-01 T -7.643e-01 BWa -5.874e-05 CAR 1.573e-04 BWe -5.874e-05	**Full model** Adj. R^2 = 1.000 Softness ~ BWa + CAR + CW + BWe + SRWa + SRAa + SRWe + SRAe + TCC Intercept 4.583e-01 BWa -2.020e-04 CAR 7.400e-05 CW 1.770e-04 BWe -2.020e-04	**Full model** Adj. R^2 = 1.000 Warmth ~ CW + BWa + CRR + T + CAR + BWe + TCC Intercept 7.112e-01 CW 9.300e-05 BWa -4.600e-05 CRR -2.685e-01 T 4.277e-01

SRWe	1.113e-02	SRWa	1.780e-02	CAR	-5.400e-05
SRWa	1.113e-02	SRAa	-6.510e-04	BWe	-4.600e-05
CW	1.506e-04	SRWe	1.780e-02	TCC	-7.453e-03
TCR	-4.460e-11	SRAe	-6.510e-04		
Qmax	-3.882e-04	TCC	1.027e-03		
TCC	8.946e-03				
Reduced model		**Reduced model**		**Reduced model**	
Adj. R^2 = 0.901		Adj. R^2 = 0.941		Adj. R^2 = 0.901	
Smoothness ~ T + BWa + CAR + BWe + SRWe		Softness ~ BWa + CAR + CW + BWe		Warmth ~ CW + BWa + CRR	
Intercept	6.706e-01	Intercept	5.368e-01	Intercept	4.832e-01
T	-2.266e-01	BWa	-1.910e-04	CW	3.710e-04
BWa	-4.600e-05	CAR	7.000e-05	BWa	-6.900e-05
CAR	1.110e-04	CW	1.650e-04	CRR	-3.040e-01
BWe	-9.800e-05	BWe	-2.260e-04		
SRWe	1.073e-02				

All the existing FTT experiments in our database were aggregated and valid comfort indices (values between 0-1) were considered. As shown in Table 2-3, to predict active smoothness, the model uses 13 fabric indices and 9 fabric indices are required for prediction of active softness, which includes some indices measured in wale (a) and course (e) directions that have equal coefficients in the model. These models appear to be exact reconstructions with 100% success rate on new measurements with the FTT. To determine the most important indices, reduced models with still R^2>0.9 have also been determined. To achieve that, only the first 6 indexes (CAR, BWa, TCR, CW, T, SRWa) are required for smoothness and 4 indices (BWe, CW, CAR, BWa) for softness.

As can be seen, the FTT **smoothness** index is governed first by compression properties; high value compression average rigidity CAR and compression work CW lead to smoother samples. Next, higher bending work BW make a sample less smooth. Thermal properties also play a role in smoothness with high TCR/TCC indices leading to a smoother sample, while thicker samples are considered less smooth. Among the roughness indices, only the surface roughness wavelength SRW is required in the reduced model, and it leads to a smoother fabric. It is interesting to note that the friction coefficient SFC is not included in the reduced model, while in the full model the expected behaviour of high SFC making the sample less smooth is present.

For **softness**, high-value CW and CAR make a sample softer. Bending work BW is however very important for the softness and high BW makes the sample less soft. The other terms in the general model are secondary effects in the FTT softness model. **Warmth** active model is made up of nine terms for full model, but only two terms i.e. CAR and T are needed to achieve high response of variability around the mean (adj. R^2 = 0.983). Higher compression rigidity reduces the warmth and the thicker the fabric, the warmer it is. Several fabric indices could be correlated, hence there is a possibility to switch them in the model. Nevertheless, only the highly correlated (R>0.9) can be considered for that.

2.4.2 Self-correlation of indices

Having mentioned the correlated indices, Table 2-4 tabulates the coefficient of determination (adjusted R^2) for the relationship between the indices with their p-values. We only mention significant correlation $p<0.01$. Many interesting correlations can be observed. Indices that are almost interchangeable require high R^2. It can be seen that this is the case for TCC and TCR which are highly correlated to each other with a strong positive relationship, $R^2=0.98$. Other indices are not as strongly correlated, though BARe and BWe are still highly correlated, while this is strangely not the case for BARa and BWa, $R^2=0.33$. We have to conclude that of all the indices, only TCR seems unneeded as it can be replaced by TCC. All other indices have their own specific contribution in how handle would be perceived. Nevertheless, many of the indices have strong significant correlation with another index when seen over all samples we have measured over the years, but with $R^2 < 0.85$. Qmax is CW and T dependent in negative manner. The thickness influence is to be expected. Higher compression work must often relate to more material in the bulk of the textile that is lowering the conductivity (e.g. less air), showing hence as an effect on Qmax. TCC, TCR and CW are also positively correlated with T, which was to be expected. CAR vs RAR, BWa vs BWe, BARe vs BWe, and BARa vs BARe are also all correlated to each other, though with lower R^2 (as low as 0.41). Other relationships between the indices are shown in the table below. Several correlation plots are also illustrated in Figure 2-12. Note that the indices are related within the plotted range of the data. Hence, there is a possibility that a different way of connection between indices might come up if the range given by the fabrics are different.

Table 2-4 Coefficient of determination for the correlation amongst the FTT fabric indices derived from more than 3000 runs of FTT

		Adjusted R^2	p-value
TCC	0.613 + 0.983TCR	0.978	<0.001
BARe	14.092 + 0.168BWe	0.830	<0.001
CW	-425.583 + 1591.764T	0.743	<0.001
BARa	126.096+ 0.704BARe	0.743	<0.001
Qmax	955.226 – 0.220CW	0.644	<0.001
Qmax	1041.605 – 316.690T	0.583	<0.001
TCC	33.262 + 12.709T	0.549	<0.001
TCR	26.088 + 26.424T	0.530	<0.001
CAR	-162.743 + 0.711RAR	0.511	<0.001
BWa	416.024+ 0.912BWe	0.406	<0.001
SRWe	1.166 + 0.013SRAe	0.382	<0.001
SRWa	1.838 + 0.017SRAa	0.337	<0.001
BARa	23.011 + 0.169BWa	0.328	<0.005
BWa	566.999 + 551.005T	0.287	<0.001
SFCa	0.170 + 0.350SFCe	0.276	<0.001
SRAa	21.745 + 0.944SRAe	0.250	<0.001
SRWa	0.949 + 1.138SRWe	0.242	<0.001

2.4.3 Discussion

From the correlation between the indices, we learn that textiles are very diverse, and that all indices, except for TCR, would need to be measured to determine the handle. Depending on the type of fabrics considered, the relationships shown in Table 2-4 could be strong, or absent. It would hence be an option to look for a sample set to the correlation between the fabric indices mentioned in Table 2-4, and if the R^2 value is >0.9, combine them as a single index. From Table 2-3 we learn that in the FTT models, all 'e' and 'a' indices are combined equally, so they have the same weight in the model. In light of the found correlations, this is unexpected, but probably the only option if one wants a single model for all fabrics. The ideal situation would probably be that one fingerprints samples, and creates models valid for a specific region only. For example, this would allow for models in the case that SFCa and SFCe are comparable, so SFCa/SFCe ≈ 1 as opposed to fabrics with very different friction between them. Figure 2-13 shows examples of such fingerprints for several knitted and also mattress ticking fabrics for selected indices obtained with the surface measurement module of FTT. The values given from the FTT are normalized to a scale of 1-10 which is based on maximum and minimum values of each index obtained from analysing our big database of FTT experiments. The selected range are shown in Table 2-5. The shaded region in the plots shows the range that is covered by the fabric properties of that type of fabric. Notice that the region covered by the knitted fabric is smaller when compared to that of mattress ticking fabric. The SRA of the mattress exceeds the maximum range of 10 used in the spider plot which is due to two reasons, i.e. i) the maximum/minimum range used to fingerprint SRA is more narrow as it is determined based on common fabrics tested, and ii) mattress ticking fabric has specific surface structure that is not handled correctly by the FTT algorithm that determines SRA. In this case, it is most likely that the mattress fabrics are out of the range for the common fabrics tested by FTT, thus the values for several indices blow up. A model tailored to the type of fabrics, so in other words, valid within a specific fingerprint region, might be needed as the fabrics will not possess the same tactile feel as common fabrics do. In the further thesis, we will consider fabric samples which can be expected to follow the same handle model, negating the need to create different models.

Table 2-5 Selected maximum and minimum values for FTT fabric indices

FTT fabric indices	unit	minimum value	maximum value
BARa	gf mm rad^{-1}	0	1000
BARe	gf mm rad^{-1}	0	1000
BWa	gf mm rad	0	2000
BWe	gf mm rad	0	2000
T	mm	0	2
CW	gf mm	0	2500
CRR	-	0	1
CAR	gf cm^{-2} mm^{-1}	0	15000
RAR	gf cm^{-2} mm^{-1}	0	45000
TCC	10^{-3} W m^{-1} °C^{-1}	0	100
TCR	10^{-3} W m^{-1} °C^{-1}	0	100

Qmax	W m^{-2}	200	1400
SFCa	-	0	1
SFCe	-	0	1
SRAa	μ m	0	300
SRAe	μ m	0	300
SRWa	mm	0	100
SRWe	mm	0	100
RCD	mm	0	1
RRD	mm	0	1

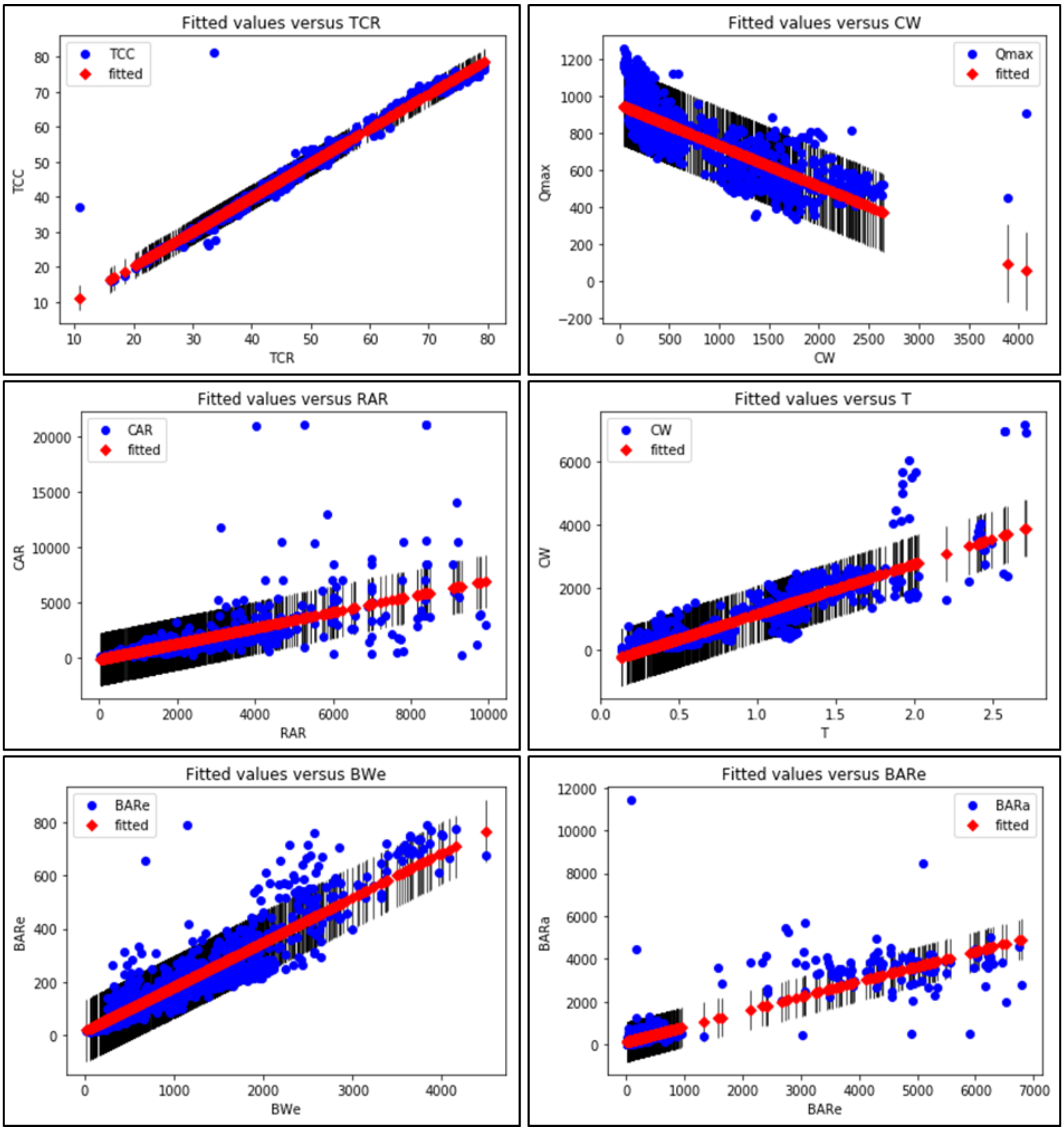

Figure 2-12 Correlation plots showing relationship between several indices

Figure 2-13 Example of fingerprints showing selected indices for several knitted (left) and mattress ticking fabrics (right)

2.5 FTT extended handling guidelines and practical information

Since FTT is considerably new in the market, no standard is yet available and the only reference for users is brief guidelines by the manufacturer. Having done the experiments for more than 100 types of samples on FTT within the Touché project, the gathered experiences are reported in here especially on handling of the device. Even though there are a number of articles relating to the FTT, none have included additional information on the handling of it, while this information is invaluable to the users in optimizing the usage of the device. Several important notes are given as follows.

i. As stated in the manual document, the sample should be in an L shape with the said dimension. It is advisable to clearly note the direction of the fabric (warp/weft or wale/course) and also the sides (outside/inside) before cutting.

ii. Cutting procedure is best to be conducted using a pressure cutting machine with an L-shaped mould specifically tailored for this test.

iii. For every batch of fabric sample, it is highly recommended to first perform a sensor check. Start with the self-check command which can be found under the 'run' menu bar. After this test is finished, all the indicators in the pop-up window should appear in green colour if the sensors are working well within the specified range. The device is only useful when the sensors are in good working condition.

iv. In the author's opinion, the self-check command is not sufficient for the calibration. Hence, another method to check the functionality of the sensors was initiated to ensure that all sensors in the two directions (warp and weft) of the test are coherent. The method is called **single leg or single arm test**, where one performs a preliminary test using rectangular strips of standard yellow samples provided by the manufacturer, instead of the usual L-shape in the actual test. The test is done five times in each directions. During the measurement, while one direction is fed by the sample, one is left bare. Hence, one can verify that the sensors give a 0 value for the unused direction. If not, it means that the sensors are picking up other values which will make them incompetent for the actual test. The manufacturer has stated the values of BW=580, T=0.63, Qmax=980 and SFC=0.3 with tolerance of 10% for the standard yellow sample, which are used to verify the validity of the single leg/arm test. It is advisable to create extra reference samples, which are the best woven or knitted samples to generally represent the fabrics.

v. Since the FTT is not provided with a zero-point thickness calibration, a further simple calibration method is recommended. For that, FTT must be run without any sample in order to see what are the values it picks up and next several rigid bodies (plates) are to be used for which FTT is expected to give consistent values. The plates could be a square of 11x11 cm and placed on the bottom plate of the FTT where the compression sensor will do the measurement. Small deviation of less than 0.02mm can be tolerated. In the author's experience, if the deviations in thickness measurement is more than 0.02mm on rigid bodies, it can be resolved by extensive cleaning using water and non-abrasive towel for the lower and upper FTT plates. This device relies on its sensors for the measurement. Hence, it is necessary to put extra attention on checking the reliability of the sensors to ensure the obtained results can be trusted.

vi. A typical use of the FTT is to compare comfort of samples, e.g. 10 sample A and 10 sample B, of which 5 are used for each side. The official use of the FTT is then to test sample A first, obtain a comfort fingerprint, then sample B, each with their own .ftt file, and compare the results. However, samples of a batch should be tested randomized so as to avoid time based effects. This means that samples of A and B will be tested in a mixed fashion, and only afterward we extract and analyse the different sample sets.

vii. It is a good practice to create a spreadsheet log file for every batch of samples that is tested. The log file should contain the corresponding sample name as in the FTT (.ftt) file, sample type and number, sides of the fabric and additional information such as date and the name of the operator. These are really useful for future references.

viii. It is also recommended to test 10 samples for each type and side of the fabric. Although the current guidelines suggest only five, based on author's experience, 10 is the minimum to be sufficient to run the statistical analysis later on.

ix. Another important note, FTT contains a hot upper plate, which heats up during testing. Normally, thin woven fabric would raise the temperature quicker than knitted and thick ones. Hence, once the bottom plate reaches 10°C above the room temperature, one should allow the plate to cool down, so as to avoid temperature dependent changes in the textile.

x. Moreover, the results should be carefully interpreted in the event of thicker fabrics, terry and fabrics with irregular surface patterns as part of the results might be unusable.

xi. Thin knitted fabrics may also cause problems, particularly those with curled or rolled edges as they are difficult to be correctly positioned on the device platform, thus making the results less trusted.

xii. Finally, as the roughness sensor is a small pin, no atypical texture should appear above the roughness sensor, or the roughness results will not be valid for the sample overall.

2.6 Comparison on measurement of selected FTT single index with common test methods

This study uses the FTT, but focuses only on the index measurement for thickness, bending and friction. The results obtained from the FTT are compared with that of the existing techniques as described in standard methods or some other methods explained below. The findings from this study serve as an indicator to check the reliability and comparability of the FTT as it would determine how far singular FTT results can be used to replace the current standard techniques to draw conclusions for the measured properties.

2.6.1 Thickness

Thickness is a common physical property evaluated in many fields including textiles. In textiles, thickness can influence the comfort sensation as it is related to heat dissipation and air permeability through fabrics (Amrit, 2007; Hatch et al., 1990). This study uses the FTT, but focuses only on the thickness index, and also on thickness gauge for measurement with standard method (ISO 5084: 1996 (E)) (European Committee for Standardization, 1996).

2.6.1.1 Materials and methods

A total of 11 fabrics were prepared to be tested using FTT and thickness standard method. The fabrics have different fibre composition and some of them are imparted with water and oil repellent finish. Table 2-6 shows the details of the fabrics.

Table 2-6 Fabrics characteristics

Fabric	Fibre composition	Weight (g/m^2)	Warp linear density (tex)	Weft linear density (tex)	Fabric density (per cm)	Fabric construction	Finishes
A	50% nomex, 50% viscose	269.18	22/2	22/2	32 x 22	Twill 2/1	Water and oil repellent
B	50% kermel, 50% viscose	253.44	22/2	22/2	32 x 22	Twill 2/1	Water and oil repellent

C	70% kermel, 30% viscose	228.74	20/2	19/2	32 x 22	Twill 2/1	Water and oil repellent
D	50% nomex, 50% viscose	253.56	22/2	22/2	32 x 22	Twill 2/1	-
E	69% nomex, 31% wool	242.72	17/2	18/2, 13/4	32 x 22	Combination twills	-
F	50% m-aramide, 50% lenzing FR (flame retardant)	268.64	24/2	24/2	32 x 22	Twill 2/1	-
G	50% m-aramide, 48% lenzing FR (flame retardant), 2% carbon-based fibres	262.82	23/2	23/2	32 x 22	Twill 2/1	-
H	70% m-aramide dope dyed, 30% viscose	220.08	20/2	20/2	32 x 22	Twill 2/1	Water and oil repellent
I	100% polyester	293.86	50/2	20/1	36 x 25	Twill 4/1	-
J	100% cotton	281.88	50/2	20/1	36 x 25	Twill 1/4	
K	50% cotton, 50% polyester	202.72	30/1	30/1	12 x 16	Knitted – single jersey	-

By using a thickness gauge, the thickness of the fabrics was measured according to the ISO 5084:1996 (E), standard method for determination of thickness of textiles (European Committee for Standardization, 1996). Following the standard, the fabrics were placed in between the circular presser foot and the reference plate of the thickness tester. The area of the presser foot is approximately 2000 mm^2 with 1 kPa pressure. Then, the gauge reading was taken after 30 seconds at different areas on the samples for at least five times. After that, the mean was calculated to be used in the analysis.

The same fabrics were also tested on FTT. In FTT, thickness is part of the compression module where the value is recorded together with the pressure exerted when the fabric is sandwiched between upper and lower plates. The compression sensor measured the compression forces and at the same time the laser distance sensor recorded the distance between the two plates which were then converted to sample thickness. The reading for thickness is given when the pressure is at 4.14 kPa or 41 gf/cm^2 (ASTM International, 2015; Hu et al., 2006; Liao et al., 2014).

It is important to note that all the samples were conditioned at 20°C ± 2°C and relative humidity of 65% ± 4% for at least 24 hours prior testing. The results obtained from both methods were then compared and analysed.

2.6.1.2 Results and discussion

FTT software computes the results for 13 indices simultaneously, plus the handle value of the fabrics. However, for this study, only the index related to thickness is emphasized. FTT gives thickness results in millimetre (mm). Similarly, the standard method yields the value in the same unit although the measurement methods were different. Table 2-7 shows the results from

FTT and also thickness test from standard method. FTT measures the outside and inside of the sample and gives two distinct readings for thickness even for the same piece of fabric sample. However, statistical analysis confirms that there are no significant differences for both sides thickness reading of a specific fabric type (p-value > 0.05). Hence, the values for inside and outside are averaged out for the correlation analysis. A t-test is conducted to examine whether the measurements are different between both methods and it shows significant differences (p-value < 0.05) between the thickness measured by FTT and the standard method. Correlation analysis of the measurements also yields the result that they are however correlated to each other (Pearson's correlation coefficient = 0.97).

In Figure 2-14 the thickness measurement of FTT and standard method is displayed in a scatter diagram with a regression line drawn on it. It shows that both measurements are highly positively correlated in linear relationship and the line fits most of the data (R^2=0.95). The differences in readings for FTT and standard method ISO 5084: 1996 (E) are the results of the different pressure used over a different contact area. The pressure is 1 kPa for the standard method and 4.14 kPa in FTT, which interacts differently with the compression rigidity of the fabrics. Due to the higher pressure on the sample and the bigger surface area during compression in FTT, the readings given are consistently lower than that of standard method. However, the intercept at y=-0.2341 is unexpected. The FTT measurement data for compression is investigated as in Figure 2-15, which shows a measurement of sample K (FTT thickness 0.67, standard method thickness 0.84). From the figure, it can be clearly seen how the thickness value reduces under increasing pressure. At 1 kPa or approximately 10 gf/cm^2, FTT gives 0.75 mm thickness. Focusing on the lower pressure, it is observed that the compression pressure starts to increase around 0.85, consistent with the standard method value. The graphical data does show that when there is no contact yet with the fabric, the compression pressure is already over 0.25 kPa, indicating that the sensor used has an accuracy around 0.25 kPa which might explain why 4.14 kPa is used to set the FTT thickness.

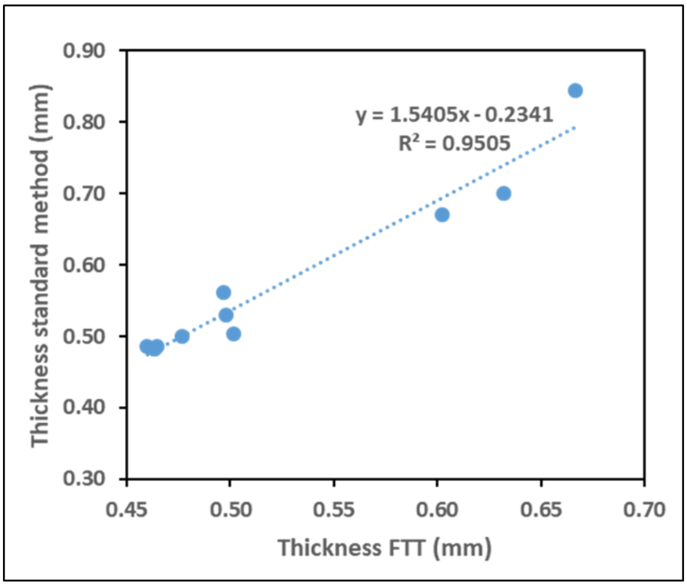

Figure 2-14 Correlation between thickness FTT and thickness standard method

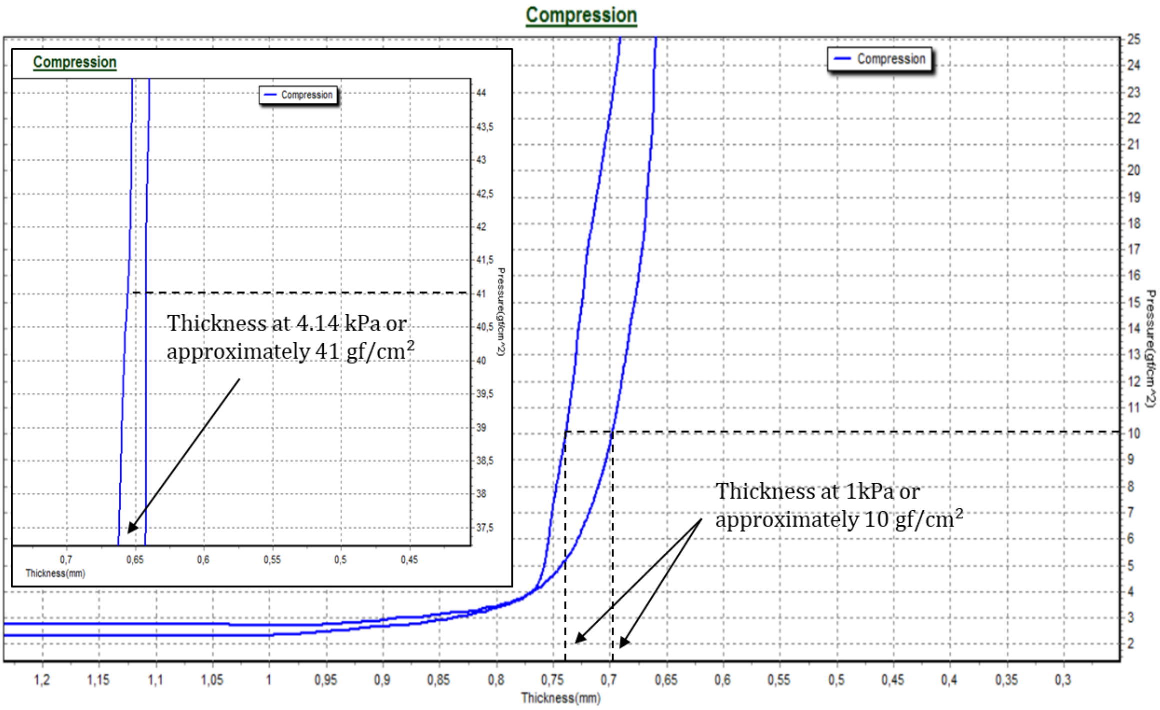

Figure 2-15 Measurement data of compression for sample K (screenshot from FTT software)

Since the FTT is not provided with a zero-point thickness calibration, an investigation is done to determine whether there is any shift in zero point of the FTT. First, the FTT was run without any sample on it in order to see what are the values it picks up. Next, several rigid bodies were measured for which FTT is expected to give consistent values. Results from this showed the FTT picks up 0 mm thickness when no sample was present and a very small deviation of 0.01 mm was observed for a 1 mm thick rigid plate. This is as projected, as for a rigid plate no thickness changes are expected at 1 kPa versus 4.14 kPa. Although the deviation is very small, textiles cannot be expected to behave the same way as the factors like hairiness and surface contour would give different impact to the measurement. Hence, it can be concluded that there is no zero shift in the FTT, provided the operator performs regularly a thickness check with calibration rigid bodies, as the author did here. Based on experience, deviations in thickness measurement > 0.02 mm on rigid bodies with the FTT can be resolved by extensive cleaning of the lower and upper FTT plates.

However, despite the differences in the measurement methods, a very good correlation is found for the selected samples, though the found regression line will not be universal for all fabrics, but will instead depend on their compression rigidity. Hence, for fabrics outside the tested range of approximately 0.45 – 0.85 mm thickness or with different compression rigidity, a new regression curve is needed before solely depending on the FTT for thickness measurements and correcting for the higher pressure applied.

2.6.2 Bending

Bending behaviour reflects the stiffness property of textiles which also influences the smoothness sensation, thus it would also contribute to the overall comfort perceived by humans. It is one of the basic parameters which are decisive for sensorial comfort along with compression, elongation, dimensional stability etc. (Kim, Takatera, & Sugiyama, 2014; Kocik et al., 2005). This study uses the FTT, but focuses only on the bending module, and also bending tester for the measurement with standard method BS 3356-1990 (British Standard Institution, 1990).

2.6.2.1 Materials and methods

A same set of fabrics as in thickness experiment was used, see Table 2-6. The fabrics were tested with FTT and also standard method for bending. Bending measurement was performed based on BS 3356-1990 standard (British Standard Institution, 1990). For this test, rectangular samples measuring 2.5 × 20 cm were prepared so that the length is parallel to the direction to be tested. Five warp and five weft pieces were tested for each type of fabric in this experiment. The samples were glided on the fixed-angle flexometer which is based on the cantilever principle. According to Peirce (Peirce, 1930a), bending length, C is the length of rectangular strip of material which will bend under its own mass to an angle of 7.1°. For ease of measurement, this method uses the cantilever length corresponding to the angular deflection θ = 41.5°, so that the bending length is half of the cantilever length as shown in the following equation. Hence, the bending length was read from the ruler when the tip of the sample touched the red line of 41.5° on the apparatus (see Figure 2-16). The higher the bending length, the stiffer the fabric is.

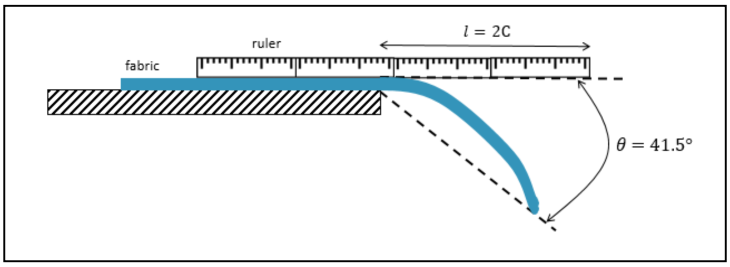

Figure 2-16 Schematic diagram of bending test according to BS 3356-1990 standard method

Bending length C is given by the calculation (1)

$$\mathrm{C} = l\left(\frac{\cos(\theta/2)}{8\tan\theta}\right)^{1/3} = l/2, \quad (1)$$

where we used θ = 41.5°, and l is the sample overhanging length at that angle. By using the appropriate mean value, the flexural rigidity (G) of the fabrics is determined in the standard using formula (2)

$$\mathrm{G} = 0.10\ \mathrm{M}\ \mathrm{C}^3\ (\mathrm{mg\ cm}) \quad (2)$$

where C is the bending length (cm), and M is the fabric mass (g/m^2). In the standard method, the unit is not given in a standard unit (SI). With SI units, the flexural rigidity of a plate is the force couple (Nm) required per width (m) to bend the plate in one unit of curvature (1/m), and hence has general unit for a plate of Nm.

Table 2-7 Thickness and bending results from FTT and standard methods

Fabric	Side	FTT Thickness (mm)	FTT BAR (warp) (10^{-4} Nm rad^{-1})	FTT BAR (weft) (10^{-4} Nm rad^{-1})	FTT BW (warp) (10^{-4} Nm rad)	FTT BW (weft) (10^{-4} Nm rad)	ISO 5084:1996 (E) (thickness, mm)	BS 3356-1190 (bending) C (warp) (cm)	C (weft) (cm)	G (warp) (mg cm)	G (weft) (mg cm)
A	Inside	0.48 ± 0.03	22.72 ± 1.29	23.94 ± 1.77	182.56 ± 6.73	198.97 ± 4.06	0.50 ± 0.01	3.14 ± 0.06	2.82 ± 0.11	833.36 ± 0.01	605.26 ± 0.04
	Outside	0.47 ±0.02	23.89 ± 1.42	26.11 ± 3.01	187.49 ± 9.73	212.73 ± 15.20		2.28 ± 0.09	2.91 ± 0.07	319.04 ± 0.02	665.03 ± 0.01
B	Inside	0.50 ± 0.03	24.33 ± 1.86	21.09 ± 2.18	212.76 ± 14.41	175.28 ± 9.55	0.50 ± 0.01	3.14 ± 0.08	2.68 ± 0.12	784.63 ± 0.01	487.84 ± 0.04
	Outside	0.50 ± 0.03	23.67 ± 2.01	23.23 ± 2.22	194.18 ± 13.44	188.94 ± 8.87		2.68 ± 0.07	2.70 ± 0.06	487.84 ± 0.01	498.85 ± 0.01
C	Inside	0.47 ± 0.02	44.72 ± 5.81	27.49 ± 1.73	359.69 ± 28.02	236.65 ± 17.33	0.49 ± 0.01	4.09 ± 0.10	3.31 ± 0.07	1564.99 ± 0.02	825.77 ± 0.01
	Outside	0.46 ± 0.02	39.98 ± 3.38	27.83 ± 2.22	313.89 ± 28.84	238.11 ± 17.15		3.59 ± 0.14	3.46 ± 0.08	1058.34 ± 0.06	947.48 ± 0.01
D	Inside	0.47 ± 0.02	18.38 ± 1.84	19.77 ± 1.78	130.40 ± 6.05	136.73 ± 2.63	0.48 ± 0.00	2.38 ± 0.05	2.18 ± 0.04	341.83 ± 0.00	263.60 ± 0.00
	Outside	0.46 ± 0.02	18.77 ± 1.45	17.35 ± 2.19	140.94 ± 5.15	127.47 ± 7.17		2.07 ± 0.08	2.17 ± 0.08	224.90 ± 0.01	258.20 ± 0.01
E	Inside	0.46 ± 0.02	19.01 ± 0.68	16.25 ± 1.51	117.14 ± 6.32	109.24 ± 6.26	0.48 ± 0.01	1.86 ± 0.03	2.07 ± 0.04	156.19 ± 0.00	213.73 ± 0.00
	Outside	0.47 ± 0.02	14.73 ± 1.33	17.74 ± 1.23	94.46 ± 4.15	120.78 ± 4.03		1.98 ± 0.03	2.02 ± 0.03	188.41 ± 0.00	200.06 ± 0.00
F	Inside	0.60 ± 0.03	21.36 ± 1.51	22.20 ± 2.10	152.09 ± 7.00	145.90 ± 10.08	0.67 ± 0.00	2.62 ± 0.03	2.43 ± 0.05	483.14 ± 0.00	384.28 ± 0.00
	Outside	0.60 ± 0.03	21.41 ± 3.94	25.27 ± 1.66	135.40 ± 6.89	165.10 ± 8.38		1.97 ± 0.05	2.45 ± 0.02	205.39 ± 0.00	395.07 ± 0.00
G	Inside	0.49 ± 0.02	23.39 ± 1.77	23.37 ± 1.13	174.59 ± 6.47	173.70 ± 10.21	0.53 ± 0.01	2.96 ± 0.07	2.66 ± 0.07	681.61 ± 0.01	493.26 ± 0.01
	Outside	0.50 ± 0.02	22.03 ± 1.41	25.19 ± 1.51	158.84 ± 7.97	188.72 ± 4.36		2.23 ± 0.09	2.75 ± 0.07	291.46 ± 0.02	543.61 ± 0.01
H	Inside	0.45 ± 0.03	21.15 ± 2.10	17.27 ± 1.44	177.14 ± 12.21	136.71 ± 9.93	0.49 ± 0.01	2.88 ± 0.11	2.63 ± 0.02	525.72 ± 0.03	401.50 ± 0.00
	Outside	0.46 ± 0.03	20.56 ± 1.22	18.23 ± 1.09	164.27 ± 11.47	141.76 ± 7.43		3.18 ± 0.09	2.58 ± 0.07	707.72 ± 0.02	375.76 ± 0.01
I	Inside	0.50 ± 0.01	25.06 ± 1.87	20.74 ± 1.67	163.37 ± 5.50	168.91 ±10.52	0.56 ± 0.01	1.95 ± 0.02	2.32 ± 0.10	217.89 ± 0.00	366.95 ± 0.03
	Outside	0.49 ± 0.01	18.72 ± 2.71	24.29 ± 3.72	129.69 ± 7.75	190.54 ± 10.86		2.12 ± 0.06	2.18 ± 0.12	279.99 ± 0.01	304.45 ± 0.05
J	Inside	0.64 ± 0.01	25.12 ± 1.38	19.29 ± 1.04	185.61 ± 9.64	131.34 ± 4.83	0.70 ± 0.01	2.57 ± 0.07	1.67 ± 0.04	478.48 ± 0.01	131.28 ± 0.00
	Outside	0.63 ± 0.01	23.11 ± 1.41	24.64 ± 1.38	178.76 ± 5.48	144.96 ± 6.00		1.90 ± 0.04	2.01 ±0.06	193.34 ± 0.00	228.05 ± 0.01
K	Inside	0.67 ± 0.02	10.24 ± 1.81	8.78 ± 1.10	55.96 ± 3.08	41.11 ± 1.71	0.84 ± 0.02	1.00 ± 0.04	1.19 ± 0.05	20.27 ± 0.00	33.73 ± 0.00
	Outside	0.66 ± 0.02	9.56 ± 1.77	10.34 ± 2.03	52.94 ± 3.25	47.39 ± 3.30		1.61 ± 0.06	0.73 ± 0.06	84.60 ± 0.00	7.81 ± 0.00

Bending in the FTT is expressed as bending work (BW) and bending average rigidity (BAR), which are both categorised with the bending module. The bending bars in FTT are placed at the same level as the lower plate and can be pushed downwards to exert a bending force during the test (see Figure 2-7). Force sensors are positioned under the bending bars to record the dynamic bending forces which are then converted into a bending moment. A graph of the moving bending angle of the sample (which has maximum value of 1.05 radian) versus bending moment (gf mm) is obtained (see Figure 2-17), and the integral of this curve over all angles is reported as the BW parameter, while the slope of this curve for the centre 60% of the bending moment is reported as the BAR parameter (Liao et al., 2014). This instrument takes angle dependent bending into account, while the standard method BS 3356-1990 only measures bending at 41.5° or 0.724 rad in one direction of bending which means the fabric bends under its own weight. The formulae for BAR (unit gf mm /rad) and BW (unit gf mm rad) are as follow (3);

$$\mathrm{BAR} = \frac{\mathrm{M(R_C)} - \mathrm{M(R_D)}}{\mathrm{R_C} - \mathrm{R_D}}, \;\; \mathrm{BW} = \int_0^{\mathrm{R_B}} \mathrm{M}\,(\beta)\mathrm{d}\beta, \quad (3)$$

where M(β) is the measured bending moment at angle β for the sample of 11 cm width, and R_D to R_C are the angle values at 20% and 80% of maximum bending moment M_B obtained at maximum angle R_B=1.05 radian.

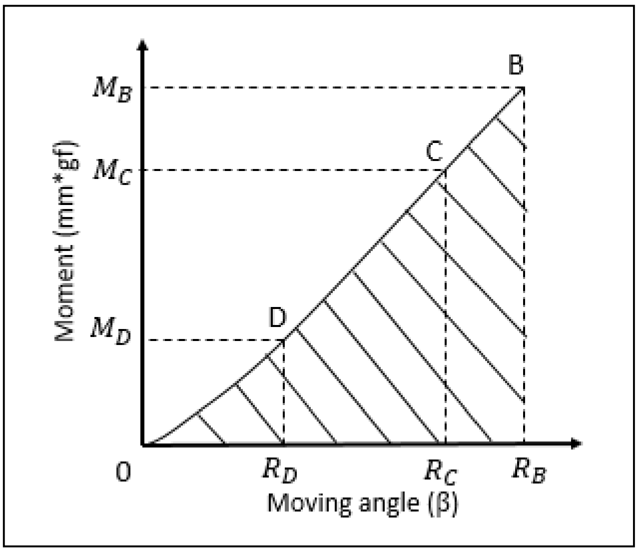

Figure 2-17 Calculation diagram of BAR and BW indices

2.6.2.2 Results and discussion

FTT software computes the results for 13 indices simultaneously, plus the handle value of the fabrics. However, for this study, only the indices related to bending were emphasized. The two FTT indices related to bending; BAR and BW, have the units of Nm rad^{-1} and Nm rad respectively, in contrast with the unit given by the standard method which is in centimeter (cm) for bending length, C, and mg cm for flexural rigidity, G. Same table with thickness results, Table 2-7 above also shows the results from FTT and bending test from standard method.

The bending module in FTT computes the input for bending average rigidity (BAR) and bending work (BW) indices in warp and weft directions, also from outside and inside of the fabric. These two indices were compared with bending length (C) and flexural rigidity (G) obtained from the standard method measurement, as well as the MC and MCC value. The MC index is obtained by multiplying the fabric mass M with the bending length C, and for the MCC index, the mass is multiplied by its squared bending length. These two indices, MC and MCC are derivatives from G (=0.1 MC^3), included to test any other possible relationship that could be linked to bending.

Table 2-8 The Pearson correlation values for outside and inside warp and weft bending parameters of the tested fabrics

Outside warp						
	BAR	BW	C	MC	MCC	G
BAR	X	0.99	0.78	0.86	0.84	0.82
BW	-	X	0.82	0.89	0.87	0.84
C	-	-	X	X	X	0.99
Inside warp						
	BAR	BW	C	MC	MCC	G
BAR	X	0.98	0.82	0.77	0.85	0.88
BW	-	X	0.91	0.84	0.92	0.94
C	-	-	X	X	X	0.94
Outside weft						
	BAR	BW	C	MC	MCC	G
BAR	X	0.93	0.82	0.92	0.86	0.77
BW	-	X	0.93	0.96	0.96	0.90
C	-	-	X	X	X	0.93
Inside weft						
Inside Weft	BAR	BW	C	MC	MCC	G
BAR	X	0.96	0.87	0.93	0.91	0.86
BW	-	X	0.92	0.95	0.96	0.93
C	-	-	X	X	X	0.97

*X: non-relevant correlation **- correlation is already stated in other cells

The Pearson correlation or the R value indicates the strength of the interaction between the analysed indices. As can be seen in Table 2-8, the R values ranged from 0.77 to nearly 1 for all the indices compared. It is no doubt that BAR is highly correlated with BW where a high BAR would make a high BW in a linear relationship. Looking at the measurement principle of both FTT and standard methods, huge differences can be seen where FTT measures the moment or work needed to bend one radian of sample, which means the more work or moment needed to bend the sample, the stiffer the fabric is. Instead, flexural rigidity G, in the standard method measures the force needed to bend the sample in one unit curvature and C or bending length is half the overhanging length of the sample when it bends down under its own mass during the experiment. In the FTT, the sample bends over a thin bar, while the angle of bending increases as the FTT plates go down, while the amount of material being bend is constant. This allows to obtain the BW as an integration of the forces, and the BAR as a slope of the measured forces. Comparing the correlations calculated between indices from FTT and standard method, it can be observed that BW has a better correlation than BAR with the parameters obtained from the standard method. However, as highlighted in Table 2-8, BW correlates best with MC (mass of the fabric multiplied by its bending length) in two cases, while it correlates best with MCC (mass of the fabric multiplied by its squared bending length) in one case (and twice close to the MC result), and also once with G. Nevertheless, if the overall data is considered, BW is best correlated with MCC. It can be concluded that BW correlates best with the standard measurement, and specifically with the MCC value.

The best correlation of BW with MCC can be explained as follows. The formula for G is $0.1 \times M \times C^3$, so MCC is actually reducing the power of C from 3 to 2. Since bending moment B, is also regarded as flexural rigidity G times the curvature ($B = G\,k$), where k is the curvature given by $1/R_c$, with R_c the radius of the circle from where the bending curvature is formed. In a first order approximation, R_c can be considered proportional with C, so $R_c \approx a\,C$, and hence $B \approx G\,/(a\,C)$. The bending work BW in the FTT on the other hand is the average bending moment over all radians sampled by the FTT. As a consequence, the good correlation between BW and MCC is not unexpected. Figure 2-18 shows a scatter plot and the regression model of the relationship between the overall BW and MCC. Coefficient of determination $R^2 = 0.83$ demonstrates a strong fitting of the data towards the model and from that yields 0.91 as Pearson correlation value which proves a very good correlation between BW and MCC. The regression model $MCC = 1.1194\ BW - 266.1$ has an intercept at MCC at -266.1 which might have contributed to the given device tolerance of ± 10% for the FTT. It is concluded that three closely related indices, MC, MCC and G have a good relationship with BAR and BW, with small Pearson correlation R-value differences between them. Amongst all, MCC gives the best correlation for the overall data set with BW.

On a side note, the BAR derivation in the reference from the manufacturer is mathematically not so well defined. Although it still gives a very strong correlation with the other indices, this is because of the strong correlation with BW, which reduces the usefulness of BAR as a separate FTT parameter. It should however relate to the speed to which the bending moment increases as the sample bends more. Therefore, as a suggestion, it might be useful to have an automated bending tester which is able to measure the bending length in terms of the angle as an extension to the BS 3356-1990 standard. The speed of the bending length change should then in turn relate to the rigidity of the samples against bending. Thus, it would be possible to draw a better conclusion from the phenomenon underlying the principle of BAR.

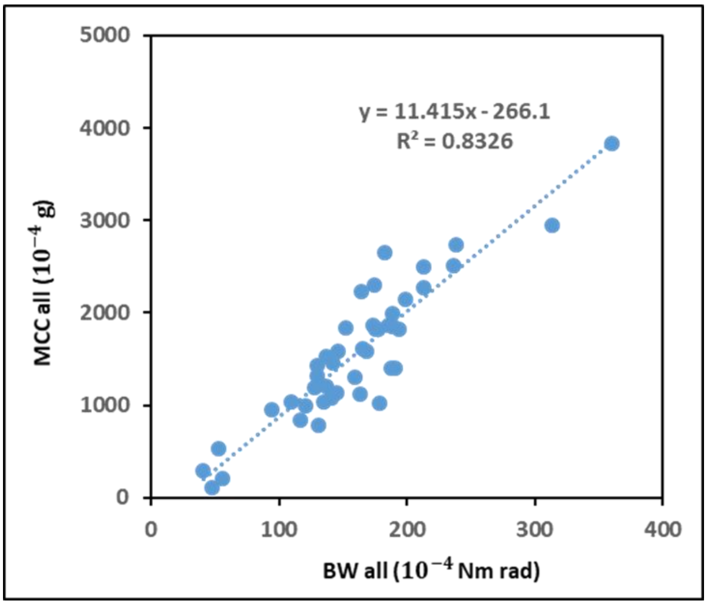

Figure 2-18 Correlation between the overall BW and MCC

2.6.3 Friction

Friction is a force resisting the relative motion between the two surfaces of objects in contact. The interaction of textiles and human most of the time happens by skin contact. This interaction provides various information on tactile properties including friction. This study aims to compare the friction measurement in FTT with the one given by the common method, i.e. rectilinear method using an extension built-up on a tensile tester, e.g. Instron device.

2.6.3.1 Material and methods

A non-homogeneous sample set consisting of 13 fabrics was used for the experiments, consisting of cellulosic, wool, polyester and polyamide with woven and knitted structures. The mass per unit area of the fabrics (EN 12127:1997) varied between 122 – 157 g/m^2 and their thickness from 0.26 to 0.66 mm (EN ISO 5084:1996). Table 2-9 shows specifications of the fabrics. The selected fabrics are in the typical range of apparel clothing fabrics.

Table 2-9 Specifications of materials for friction test

Fibre composition	**Fabric ID**	**Mass per unit area (SD), g/m^2**	**Yarn linear density (Tex)**		**Fabric density (warp/ wale x weft/ course per cm)**	**Thickness (SD), mm**	**Fabric construction and finishes**
			Warp/ wale	**Weft/ course**			
100% Lenzing™ Lyocell	A-knit-CLY	125 (2.60)	20/1	20/1	13x16	0.60 (0.02)	Knitted -Single jersey Washed on frame, no additional treatment.
50/50% cotton/Lenzing ™ Lyocell	B-knit-CO/CLY	152 (0.88)	20/1	20/1	14x20	0.64 (0.02)	
100% Lenzing™ Modal	C-knit-CMD	140 (0.63)	20/1	20/1	14x20	0.51 (0.01)	

100% cotton	D-knit-CO	157 (2.21)	20/1	20/1	15x20	0.66 (0.01)	
100% Lenzing™ Modal Micro	E-knit-µCMD	155 (1.63)	21/1	21/1	15x20	0.57 (0.02)	
100% Lenzing ™ Modal Micro	F-wov-µCMD	134 (0.63)	10/1	10/1	78x51	0.27 (0.00)	Woven - Satin 5/3 Desized and washed, no additional treatment
100% Lenzing™ Lyocell Micro	G-wov-µCLY	136 (0.61)	10/1	10/1	77x51	0.27 (0.02)	
100% cotton	H-wov-CO	135 (0.84)	10/1	10/1	75x58	0.32 (0.02)	
100% Lenzing™ Modal	I-wov-CMD	138 (0.46)	10/2	10/2	78x53	0.27 (0.01)	
100% Lenzing™ Lyocell	J-wov-CLY	131 (0.35)	10/1	10/1	77x52	0.26 (0.01)	
*100% wool	K-wov-WOOL	122 (1.16)	30/2	30/2	21x18	0.30 (0.01)	Woven – Plain weave, no additional treatment
*100% polyester	L-wov-PET	132 (0.43)	34/2	24/1	25x20	0.34 (0.01)	
*100% polyamide	M-wov-PA	150 (1.62)	44/2	22/1	22x20	0.43 (0.02)	

*adjacent fabrics used in testing of colour fastness (the specification are controlled according to ISO 105-F01/F03/F04:2001 standards.

With an addition of a platform horizontally attached to tensile tester, the friction experiment was performed following the rectilinear method which was in accordance with Amanton's Law. The law specifies that the motion of one body with respect to the other is rectilinear. The set-up of the experiment is shown in Figure 2-19. On the platform, a square metal sled of 6×6 cm was used, weighing with the addition of a weight 1106 g. The test sample is placed in between the platform and the sled. A pulley is positioned at one end of the platform which enabled a rigid string attached to the sled to be pulled horizontally by the crosshead of the tester along the platform. While one end of the string is attached to the sled, another one is to the crosshead, directly to the load cell. As the crosshead/load cell moves, the sled is pulled across the horizontal platform to which the sample is attached.

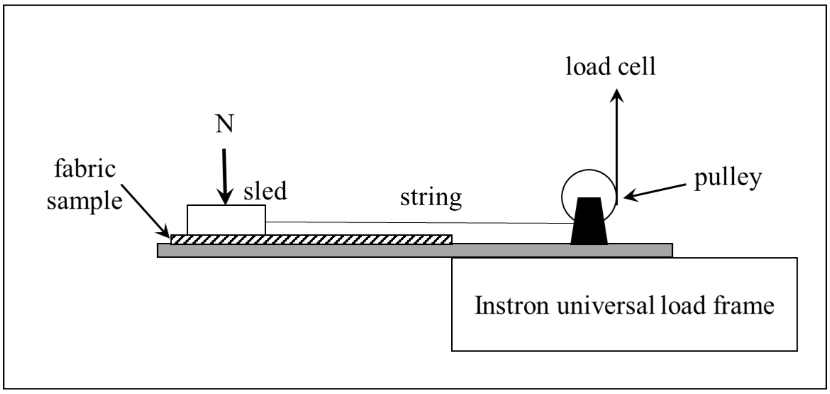

Figure 2-19 Rectilinear friction test set-up on a tensile tester

The fabrics were also tested with FTT, following the same procedure as before. However, this time, the friction measurement is examined for the comparative analysis purpose. In FTT, friction is included in the surface module, which also consists of the surface roughness measurement. It is measured at the arm-parts of the FTT as previously mentioned in section 2.3.4 above. The tester measures static and dynamic coefficient of friction (CoF), while FTT only measures dynamic. A CoF is a value that shows the relationship between the force of friction between two objects and the normal reaction between the objects that are involved, in this case fabric surface and metal surface of a sled used in the experiment setup for intron or from pressure roller in FTT. The CoF does not have any unit as it is dimensionless. It is also a scalar, which means that the direction of the force does not affect the physical quantity. The CoF is shown by $\mu = F_f/F_N$. In this equation, μ is the CoF, F_f is the frictional force and F_N is the normal force.

2.6.3.2 Results and discussion

The results from both methods are tabulated in Table 2-10. For FTT, although the device yields result of 13 indices simultaneously, only friction results are discussed here. The friction index in FTT is called SFC or surface friction coefficient which refers to the average dynamic coefficient of friction (CoF). As there was no static friction measurement by FTT, comparisons were made only with dynamics friction results from both devices.

Table 2-10 Friction results from rectilinear method (tensile tester) and FTT

	Tensile tester - friction test results			**FTT friction results**		
	Dynamic CoF warp	**Dynamic CoF weft**	**Dynamic CoF average (warp&weft)**	**SFC warp**	**SFC weft**	**SFC average (warp&weft)**
A-knit-CLY	0.280	0.256	0.268	0.471	0.569	0.520
B-knit-CO/CLY	0.230	0.218	0.224	0.361	0.453	0.407
C-knit-CMD	0.256	0.238	0.247	0.398	0.484	0.441
D-knit-CO	0.230	0.252	0.241	0.577	0.461	0.519
E-knit-µCMD	0.284	0.290	0.287	0.456	0.581	0.518
F-wov-µCMD	0.224	0.250	0.237	0.276	0.399	0.338
G-wov-µCLY	0.228	0.258	0.243	0.274	0.455	0.364
H-wov-CO	0.226	0.256	0.241	0.373	0.330	0.352
I-wov-CMD	0.208	0.226	0.217	0.225	0.357	0.291
J-wov-CLY	0.208	0.222	0.215	0.233	0.394	0.313
K-wov-WOOL	0.182	0.192	0.187	0.309	0.308	0.308
L-wov-PET	0.202	0.206	0.204	0.281	0.337	0.309
M-wov-PA	0.200	0.202	0.201	0.269	0.343	0.306

Correlation and regression analysis were executed in order to obtain the relationship between both methods. Table 2-11 shows the Pearson's R correlation for warp and weft and also the average value from the combination of warp and weft data. Friction is a property that results from the surface texture of the fabrics which largely corresponds to warp and weft yarn interlacement. Hence, the average combination of both data is considered. The Pearson's R yields 0.82 with $p<0.001$ for the relationship between the average of both methods. It clearly shows a high positive relationship for both methods which means that the values have a linear relationship despite the differences in the principle of measurements with the two devices. The other correlation values are not as high but still correlate with $p<0.05$. We obtained a constant lower reading for the measurement using the tensile tester. The difference in the normal forces given to the samples i.e. 140 gf in FTT and 1106 gf can normally not attribute for this. It indicates that for the same normal force we measure higher friction force in the FTT. We attribute this to the fact that in the FTT, the weight is rolling above the friction plate and hence not fixed, and the fact that the friction plate is ribbed, while the sled is smooth. An investigation on the roughness index of FTT i.e. SRW or Surface Roughness Wavelength also indicate a good correlation R=0.78 for the relationship with friction measurement of FTT i.e. SFC. The y intercept = -0.2191 (see Figure 2-20) indicates the linear relationship will not be valid for low CoF values (<0.15). The regression line fits 67% of the data as given by R^2 value.

Table 2-11 Pearson's R value for the relationship between friction measurement with FTT and tensile tester-rectilinear

		Friction–tensile tester - Dynamic CoF		
		warp	weft	average
Friction FTT - Dynamic CoF (SFC)	warp	0.65		
	weft		0.73	
	average			0.82

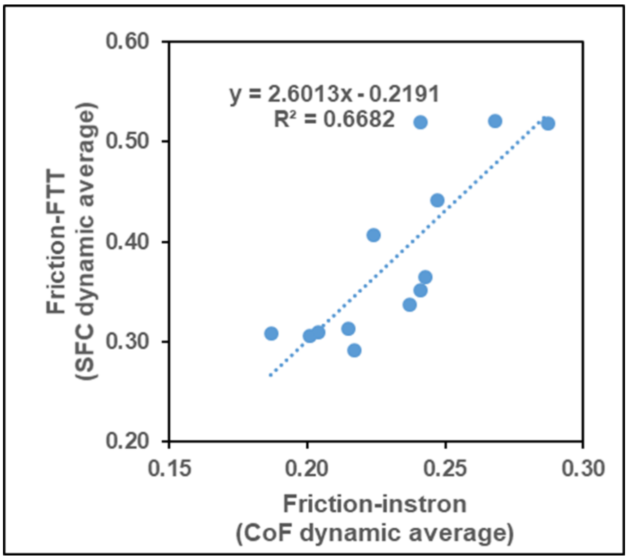

Figure 2-20 Plot Friction-tensile tester versus Friction-FTT showing positive linear relationship

2.7 Conclusion

A new device, FTT is claimed by its manufacturer as a device that can rapidly measure fabric comfort properties within its four integrated modules, i.e. thermal, compression, surface and bending. The emergence of this device brings simplicity to the testing protocol of the comfort properties as it is an all-in-one tester, thus it saves time for testing. Nevertheless, the fact that it is still considerably new, needs a further confirmation to be able to gain trust by the users or stakeholders. Therefore, the measured indices were examined and three selected indices i.e. thickness, bending and friction measurements were investigated. A comparative analysis with the common methods were done which concludes a promising hope for the device to be accepted. Although the measured data are different, strong correlation exists with the standard measurements.

The measurement of FTT was analysed and compared with the standard methods which are commonly used in the textile industry, in order to gain a better understanding on how they relate and if the FTT can be used as an alternative. As an advantage, this will reduce the testing and computing time for the companies having an FTT in their lab. Despite having differences in the principle of measurement, it is found that FTT demonstrates a significant correlation with the standard method for thickness. The Pearson's correlation, R gives 0.97. The correlation analysis indicates a very strong correlation between FTT and standard methods. Although the correlation is high, FTT should not be used as an alternative measure at the moment. A standard calibration method of the FTT would be required as an improvement for the device. FTT also demonstrates a significant correlation with the standard method for bending. BW shows the highest correlation with MCC which is at 0.91 for the overall value from warp and weft samples. The correlation analysis indicates a very strong correlation between FTT and standard method for bending. The measurement of CoF was performed using FTT and a tensile tester. The results from both devices were compared to obtain the correlation between the measurements of the two devices. Based on the analysis conducted, a positive relationship was found between FTT and the friction measurement with tensile tester, although it is lower than that of thickness and bending. The Pearson's correlation of R-0.82 was obtained for the relationship between average dynamic CoF of both methods which combined the data from warp and weft directions of the samples. These findings are significant as to estimate the reliability and comparability of the FTT towards the standard measurements. Thus, it is confirmed that the FTT measurement reflects the standard on common thickness, bending and friction measurement, for the indices measured.

No standard yet exists for FTT; thus, the handling methods are just based on the manufacturer's manual guidelines. An extensive usage of this device gives the author some additional input that will be useful for other FTT users as these have not been publicly shared by the manufacturer yet. The author found that extensive care is needed to verify the accuracy of the device sensors and reference samples must be acquired to check the consistency of the results given by the device.

The predictive models used in the FTT were reconstructed through a multiple stepwise regression analysis. These allowed us to understand how the models are composed. In Chapter 5, these models will be analysed and accompanied with a thorough discussion.

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3

Improvement on human assessment of fabric handle - A comprehensive approach for split or large set of fabrics

Knowledge is the life of the mind.

Abu Bakr as Siddique

This chapter tackles subjective hand assessment as well as the importance of it in fabric handle measurement. Due to its importance, some relevant improvements are suggested for the procedural terms in assessing large sets of samples.

This chapter is based on the publication:

Binti Haji Musa, A., Malengier, B., Vasile, S., & Van Langenhove, L. (2019). A comprehensive approach for human hand evaluation of split or large set of fabrics. Textile Research Journal, First published 24 February 2019.

3.1 Introduction

Assessment of fabric handle relies on the feel of humans. The advancement of technology and practicality of the usage of computer integrated systems do not outshine the significant use of subjective methods in assessing fabric handle. New materials are continuously discovered and enter market segments and hence become an option for laymen to choose. As fast fashion industry is growing, brands such as Zara, H&M and Primark offers great choices of clothing at relatively cheap prices. In 2016, households in the European Union (EU) spend nearly €400 billion for clothing and footwear which is about €800 per inhabitant (Eurostat, 2018). This huge sum of money fuels the clothing business and makes it rapidly grow.

Since people often buy clothes, it means that assessment on clothing preference by hand motion is also a common thing for almost everyone as we are the consumers. More often than not, the fabric handle properties are an important and decisive criterion for purchasing the fabrics, as the consumers touch and squeeze them before they buy them. The touch motion by the palm and fingers gives information about some handle attributes which are commonly used to describe fabric comfort such as smoothness, softness and warmth. To meet customer satisfaction, fabric hand shall be ensured and evaluated during fabric development by means of human panels.

Studies on this topic were pioneered by Binns (Binns, 1926b) in 1926 and continued until this present time. However, clothing manufacturers may quantify the fabric handle of their products through an in-laboratory method which is using devices such as Kawabata Evaluation Systems for Fabric (KESF) (Kawabata & Niwa, 1989), Fabric Assurance for Simple Testing (FAST) (De Boos & Tester, 1994), Fabric Touch Tester (FTT) - as seen in the previous chapter (Hu et al., 2006; Liao et al., 2014), Material Tactile Tester (MTT) (Yao et al., 2018) or using a device that measures only some features on fabric handle such as ring or pulling method (Ciesielska-Wrobel & Van Langenhove, 2012; Kim & Slaten, 1999; Strazdiene & Gutauskas, 2005; Sular & Okur, 2008) and Alambeta (Hes & Dolezal, 1989). These devices need to objectively measure the fabric properties based on their specified principles and most importantly they should be able to predict the fabric handle of a human. This is schematically depicted in Figure 3-1. The obtained values from the devices should be correlated with human touch and thus, predictive models on certain touch attributes can be generated based on the human values through the human assessment. Unlike objective assessment, human assessment is more subjective as the judgement greatly depends on the feel of a human which might be different from one person to another. In order to arrive at qualitative predictive models large sample sets are needed, requiring a comprehensive approach.

Although the subjective evaluation by humans are vast and idiosyncratic, to some extent they can agree with each other and some trends can be distinguished. In order to make the assessment results quantifiable, numerical values or scales are assigned to each fabric sensorial attribute which were discussed by Osgood and his team (Osgood, Suci, & Tannebaum, 1957). The assessment involves either ranking, paired-comparison or rating methods (Ellis & Garnsworthy, 1980; Kayseri et al., 2012; Slater, 1997).

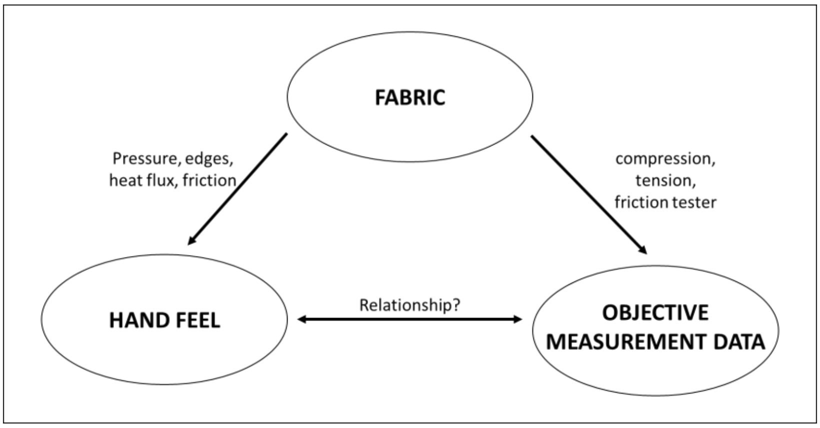

Figure 3-1 Tactile testing of fabrics via humans or machines, requires establishment of a relation between feel results and machine measurement data

Ranking is a type of assessment method in which panel members rank or order a set of fabrics according to some selected sensory attributes or descriptors such as warmth, smoothness, crispiness, etc. For instance, in case of 7 fabrics, the smoothness is ranked from score 1 for the smoothest, to score 7 - the least smooth. This method is partly similar to paired-comparison or also known as pairwise test method, but for the pairwise method, the samples are presented to the panel members in pairs (two samples) and comparison on the selected fabric attribute is made between the two samples. As the panel members compare only two samples at a time, it is believed that their focus and judgement is better than the ranking method. However, in order to complete the assessment, all the possible combinations of the samples need to be presented to the panel members one after another and after that, the result will be ranked from the most chosen ones until the least. For instance, in case of five fabrics, 10 combinations are possible but larger fabric sets lead to more combinations, following the combination formula n! / [r! (n – r)!], where n is number of samples and r is the chosen samples at one time (i.e. in this case, r=2). The pairwise assessment is impractical as it is time consuming for large sample sets, although the precision among the panel members could be better when compared with the ranking method.

The last considered method is the rating method. For this method, the tested fabric attributes are assessed on a scale e.g. 1 to 10 where normally the two extreme ends or bipolar properties of fabrics are assigned with the lowest (i.e. 1) and highest score (i.e. 10) respectively. A set of fabrics is handed to the panel members who have to identify the extremes or they might be given a reference sample as benchmark and next, assign the scores for other fabrics accordingly. Rating method has an advantage over the ranking method. Based on the given scores, the degree of differences between samples is known whereas ranking method only gives the hierarchy of the samples. However, rating method may lead to a large disagreement amongst the panel members due to unsustain focus in case of large number of samples and previous studies recommended a limitation of number of samples to only 10 (Grinevičiūtė & Gutauskas, 2004; Vasile et al., 2019). This limitation decreases the potential of this method to be practically used for a large sample set, and as 10 is the maximum number of samples, more than 10 should already be considered as a large set. Table 3-1 summarizes the advantages and disadvantages of each method. To be able to obtain more information from panels members i.e. rank of the samples and degrees of differences between them, and at the same time eliminate the errors due to human factors e.g. unable to sustain the focus for a long time or fatigue, a new approach must resolve these matters. Long testing time and fatigue are known to cause uncomfortable feeling to the assessors, however they have never been taken into account during the assessment.

Table 3-1 Summary of advantages and disadvantages for methods in human evaluation of fabric handle

Method	**Advantages**	**Disadvantages**
Ranking	Quick method – time saving	Not practical for high number of samples The degrees of differences between samples are unknown Poor way of judgement by panel members
Paired-comparison	Most accurate way for qualitative judgement as only two samples are evaluated at one time.	Very time-consuming Not practical for high number of samples The degrees of differences between samples are unknown
Rating	The results give more information – rank of the samples and degrees of differences between them.	Not practical for high number of samples

In addition to the technique used, human evaluation also raises issues such as demographic aspects (i.e. age, gender, origin/ethnicity) of the panel members, blind and non-blind assessment, expert and non-expert assessors, etc. (Ciesielska-Wrobel & Van Langenhove, 2012; Ellis & Garnsworthy, 1980; Slater, 1997). In most cases, the AATCC Evaluation Procedure 5-2011 is used which is the only documented guidelines meant specifically for subjective evaluation of fabric handle (American Association of Textile Chemists and Colorists, 2014). However, these are general guideline and not specifically tailored to a large set of fabrics. Knowing the potential of the human evaluation as to provide fundamental information especially in generating models for prediction of fabric comfort properties, a method is required to assess a large number of fabrics in a wide range, with a large pool of panel members from all around the world, testing their own set of fabrics, at their own institutions and to create good statistical predictive models. In the end, these results need to be merged synchronically, which will offer a greater use of the results in the field of tactile comfort.

There are no guidelines at the moment on how disparate tactile experiments can be combined in order to improve the predictive models. There is also an absence of relevant guidelines dealing with large set of samples or split of samples (i.e. geographic or in time). Therefore, this study aims to introduce an improved approach on conducting fabric handle assessment through a blindfolded rating method. For this purpose, three fabric sensory attributes of a non-homogeneous set of 13 fabrics for clothing differentiated among others by fabric construction and raw materials were assessed. The range of fabrics is comparable, in the sense that they are meant to be for apparel clothing. We also propose a selection method of the panel members aiming at eliminating rating discrepancies as results of their origin, age and gender. The approach in this paper is comprehensive as it includes all steps starting from selecting the panel members, sample preparation and handling, experimental and combining rate method procedures, and also analysis, as will be thoroughly explained later. The method allows to increase the datasets required to improve predictive models as it offers the possibility to train models over broader, more disparate (within reason) sample properties such as thickness, construction, mass and others.

3.2 Materials

A non-homogeneous sample set consisting of 13 fabrics was used for the experiments, consisting of cellulosic, wool, polyester and polyamide with woven and knitted structures. The mass per unit area of the fabrics (EN 12127:1997) varied between 122 – 157 g/m^2 and their thickness from 0.26 to 0.66 mm (EN ISO 5084:1996). Table 3-2 shows specifications of the fabrics. The selected fabrics are in the typical range of apparel clothing fabrics. Fabrics A-J are cellulosic which were obtained from the manufacturing company, i.e. Lenzing, Austria. Wool, polyester and polyamide (fabric K, L and M) are the standard adjacent fabrics used in testing of colour fastness in which their specifications are controlled as to conform to ISO 105-F01/F03/F04:2001 standards.

Table 3-2 Specification of the materials

Fibre composition	**Fabric ID**	**Mass per unit area (SD), g/m^2**	**Yarn linear density (Tex)**		**Fabric density (warp/ wale x weft/ course per cm)**	**Thickness (SD), mm**	**Fabric construction and finishes**
			Warp/ wale	**Weft/ course**			
100% Lenzing™ Lyocell	A-knit-CLY	125 (2.60)	20/1	20/1	13x16	0.60 (0.02)	Knitted -Single jersey Washed on frame, no additional treatment.
50/50% cotton/Lenzing™ Lyocell	B-knit-CO/CLY	152 (0.88)	20/1	20/1	14x20	0.64 (0.02)	
100% Lenzing™ Modal	C-knit-CMD	140 (0.63)	20/1	20/1	14x20	0.51 (0.01)	
100% cotton	D-knit-CO	157 (2.21)	20/1	20/1	15x20	0.66 (0.01)	
100% Lenzing™ Modal Micro	E-knit-µCMD	155 (1.63)	21/1	21/1	15x20	0.57 (0.02)	
100% Lenzing ™ Modal Micro	F-wov-µCMD	134 (0.63)	10/1	10/1	78x51	0.27 (0.00)	Woven - Satin 5/3 Desized and washed, no additional treatment
100% Lenzing™ Lyocell Micro	G-wov-µCLY	136 (0.61)	10/1	10/1	77x51	0.27 (0.02)	
100% cotton	H-wov-CO	135 (0.84)	10/1	10/1	75x58	0.32 (0.02)	
100% Lenzing™ Modal	I-wov-CMD	138 (0.46)	10/2	10/2	78x53	0.27 (0.01)	
100% Lenzing™ Lyocell	J-wov-CLY	131 (0.35)	10/1	10/1	77x52	0.26 (0.01)	

*100% wool	K-wov-WOOL	122 (1.16)	30/2	30/2	21x18	0.30 (0.01)	Woven – Plain weave, no additional treatment
*100% polyester	L-wov-PET	132 (0.43)	34/2	24/1	25x20	0.34 (0.01)	
*100% polyamide	M-wov-PA	150 (1.62)	44/2	22/1	22x20	0.43 (0.02)	

*adjacent fabrics used in testing of colour fastness (the specification are controlled according to ISO 105-F01/F03/F04:2001 standards.

3.3 New proposed method for human evaluation of fabric handle

3.3.1 Selection of panel members

A human panel consisting of 28 individuals (i.e. textile engineering postgraduate students, researchers or technical staff) was established. The group consists of 14 males and 14 females from age 23 to 56 (37 ± 9 years). They are from different origins (i.e. 8 from Asia, 5 from Africa and 15 from Europe) but all of them have stayed in Europe for at least one month before the commencement of the assessment. This pool is a mix of members who have experience in assessing fabric hand (Vasile et al., 2019) and those with no fabric hand-assessment experience. General guidelines exist for selection, training and monitoring of sensory assessors (Meilgaard et al., 2007). In our study, we use a panel of selected assessors where their finger sensitivity was screened with JVP Domes, a kit used to measure spatial acuity of skin surfaces through eight plastic gratings with equidistant bar and grooves widths (0.35, 0.50, 0.75, 1.00, 1.20, 1.50, 2.00 and 3.00 mm) (Stoelting Company, 1997). This tool is employed to quantify the tactile sensitivity of clinical patients who have nervous system disorders or injuries which impaired their touch sensory (Bleyenheuft & Thonnard, 2007; Tremblay et al., 2000). The gratings are pressed against the finger of the subject/test person (randomly in any of two orthogonal directions) and the subject has to report the orientation of the grooves and bars to the examiner. The examiner records the answer as correct or incorrect as to be used later in the calculation. This is repeated 20 times and eventually the grating gap and bars width that yield threshold performance of 75% correct discrimination (that is halfway level between chance and perfect discrimination) is determined.

For this study, the panel members were selected within the range of 0.6 to 1.8 mm discrimination performance which is calculated based on Equation 1, where g is the grating spacing, p is correct trials/number of trials, g_{high} and g_{low} refers to the highest and lowest grating spacing on which the patient responded correctly better and lower than 75% of the time, and p_{high} and p_{low} are the probability of correct response on g_{high} and g_{low}, respectively. g_{75} is the hypothetical grating spacing on which the panel member would have scored 75% had it been present (Stoelting Company, 1997). Based on the range reported in the literatures which is in average of 0.98-1.22 for normal people (Sathian & Zangaladze, 1996; Sathian et al., 1997; Stoelting Company, 1997; Van Boven & Johnson, 1994), we considered the range used here (0.6 to 1.8 mm) to be satisfactory.

$$g_{75} = g_{low} + \frac{(0.75 - p_{low})}{(p_{high} - p_{low})} (g_{high} - g_{low})$$

(Equation 1)

3.3.2 Sample preparation and handling

The sample size used for the evaluation is 20x20 cm. The size should be equal for all the samples and should not be less than the mentioned size as that would restrict the movement of the fingers and hand during the assessment. Each panel member received an untested fabric set (i.e. not used yet by another tester), to eliminate the effect of multiple handling that could modify the handle properties of the samples. The fabrics were labelled and left in a controlled room conditioned at 21°C ± 2°C and relative humidity of 65% ± 4% for at least 24 hours before the test commenced (ASTM International, 2004).

On the assessment day, the samples to be tested were placed on an equal non-metallic table (low thermal absorption) with the surface to be evaluated facing up. As the arrangement of the samples needs to be reshuffled during the assessment, it is advisable to place the samples inside of moveable cardboard blocks so that this process can be done at ease without touching the samples. The blocks with the samples were placed randomly next to each other. Flat A4 printing papers are placed in between the sample and the cardboard, to avoid any cardboard texture influence, which may occur especially in the case of thin fabrics. The samples, the cardboard with papers of 2 mm thick, and also the table started at an equal temperature as the test was conducted in a controlled climate room.

During the assessment, especially in case of large number of fabrics, the panel members will need to make some moves in order to reach the samples situated out of their arm length. Hence, it is also important to consider the ergonomic aspect of the table on which the samples are placed, especially its length and height to avoid any uncomfortable position to the panel members during assessment.

3.3.3 The blind rating method experimental procedure

Tactile feel is a multidimensional concept which involves several attributes including compression, friction, surface roughness, dynamic thermal contact property etc. (Mooneghi, Saharkhiz, & Varkiani, 2014). In this study, three fabric sensory attributes or descriptors were to be assessed i.e. smoothness, softness and warmth. These three attributes are often used to explain the judgements made on fabric handle (De Boos & Tester, 2005; Liao et al., 2014) and also included in ASTM D123 standards on terminology used to describe hand (ASTM International, 2013). Smoothness refers to a surface free from projections, irregularities or inequalities (Liao et al., 2017). The opposite property of smoothness is roughness which is described by the indentations and ridges on the fabric surface (Sular & Okur, 2007). Softness relates to the ability of the fabric to bend as fabrics that can easily bent are described as soft and the opposite property is stiff or hard. However, other than bending, properties such as compressibility and shearing rigidity are also related in the assessment of softness (Bishop, 1996). The perceived warmth or coolness of a surface is a measurement of how fast or slow heat is conducted out of the skin (Hes, Offerman, & Dvorakova, 2001) and it is the first fabric-skin contact feeling of heat exchange.

A number of 13 fabrics was used for this experiment and the details of the fabrics were described in the previous section. As several researchers suggested to limit the maximum numbers of samples tested in one session to 10 samples, a sample set larger than 10 samples could be then considered a large sample set. Our new approach complements previous research dealing with more than 10 samples and proposes a more practical approach to handle the samples.

Rating method with some improved steps was employed for evaluation as it provides more information about the samples and as it is the only way to combine results of multiple sessions as we show later. A scale from 1-10 was used where 1 and 10 were assigned for the extreme opposites of the attributes. For instance, score 1 is assigned to the roughest, stiffest and coolest sample and score 10 indicates the smoothest, softest and warmest sample, respectively. The assessment was conducted in laboratory environment with controlled temperature and humidity (20±2°C, RH 65±4%) (ASTM International, 2004) and was supervised by a test facilitator. For each fabric attribute, the panel members used their dominant hand to touch the samples (Sular & Okur, 2007). The procedures were explained by the facilitator (see Table 3-3) to guide the panel member to get the intended feeling for the specified attributes. The fabric can be grasped in many different ways, depending on the testing person as reported by other researchers (Bacci et al., 2012; Pensé-Lhéritier et al., 2006). However, we ask the assessors to use the same touch method as specified in Table 3-3 so as to gain the feel from the same gesture from all of them.

Prior the assessment day, the procedures were disseminated to the panel members. They were also reminded not to put any moisturizing cream or lotion onto their hands on the assessment day as that might affect the touch perception during the assessment. When they enter the room, first they were asked to wash their hands with a standard soap, and dry them with the provided towels (Kandzhikova & Germanova-Krasteva, 2016; Vildan Sular & Okur, 2007). Next, they were allowed to acclimatize for about 15 minutes in the room and asked to minimize the use of their hands. During this period, the test facilitator briefed the assessment procedures and the methods to the panel to ensure that the test will run smoothly. To avoid the visual influence during assessment, a blindfold was placed onto the assessor's eyes as in Figure 3-2.

Table 3-3 Touch methods and description for fabric touch evaluation

Fabric attribute to assess	**Touch method**	
warmth		Initial contact (2-3 seconds) of the finger tips to the fabric surface
smoothness		Touch the sample then lightly press and move over the sample with the fingers and the palm of the hand
softness	 	Pick up the fabric and rub it between thumb and fingertips, then squeeze the sample gently between the thumb, fingers and palm by making a fist

Figure 3-2 Fabric handle assessment by one of the blindfolded panel

As suggested by AATCC 5-2011 procedure, thermal related attributes should be the first to assess prior to other attributes, hence warmth was assessed first (American Association of Textile Chemists and Colorists, 2014). While the eyes were blindfolded, the panels first identified the extreme samples i.e. coolest and warmest, thus assigned them score 1 and 10 respectively. After that, they were asked to rate the rest of the samples using the given scale of 1-10 by comparing them with the extremes they picked earlier. Since the panel members were blindfolded, they might have difficulties to write the rating on their own, hence they may communicate with the test facilitator who will then record it on the assessment sheet on their behalf. To maintain the random position of the samples, they were rearranged before the assessment of the next attribute, this is done with the help of an available online mobile application to shuffle the sample list as to avoid any human bias. Then, assessment of smoothness and softness took place with the same procedures as in warmth. Three-minutes interval was taken in between the assessment of two consecutive fabric attributes. The panel members were allowed to rest and they could put off the blindfold during that time. It is important to make sure that they turn to the other direction as not to see the samples in order to avoid visual bias in the results.

3.3.4 Combining rate method results

There is a concern reported by previous researchers when using a high number of samples for human assessment as that has created more disagreement on the results amongst panel members (Grinevičiūtė & Gutauskas, 2004; Vasile et al., 2019). This might be associated with fatigue or lack of focus in dealing with the samples thus the panel was unable to perceptually recognize each of them. Hence, it was recommended to limit the number of samples tested in one session to 10 samples (Grinevičiūtė & Gutauskas, 2004; Vasile et al., 2019). This limitation impedes the potential of this type of assessment in giving meaningful results. Therefore, in addition to the available protocols, we improve to make them also suitable and useful for split testing (geographical or in time) as well as generally for large number of samples, i.e. more than 10 samples. Thus, the samples are split into several batches (each of maximum 10 samples) and then the test for the first batch is run. After that, for each attribute, two samples are chosen as the best and worst, hereafter called reference samples. These samples are added to the second batch of samples and then the test is run again in the second session. For the consequent batches, the same method is applied until the assessment of all batches is finished. Figure 3-3 shows an example of how 26 samples (A to Z) are divided into three batches to be tested in three sessions. For batch one, 10 sample from A to J are included. During the first evaluation session, the smoothness of the samples is assessed and sample A and J are chosen as the extremes or references i.e. the smoothest and roughest, respectively. In the second session, ten samples are tested, which includes these two sample together with eight other samples, i.e. K to R. So only 8 new samples are added, for a total of 18 after two sessions. From the second session, suppose that samples A and Q are selected as the reference by the panel members, hence these two will be included in the third batch of samples together with again eight new other samples i.e. S to Z, and tested in session three for a cumulative amount of 26 samples. Note that in this example, sample A is tested in every session as it is picked as reference in each session. Although it is assessed in three sessions, it is a good practice to always use a fresh sample for each session in order to avoid any fabric changes as results of previous touch sessions. Through this suggested blind rate method, the focus of the panels can be sustained as only a limited number of samples is used, thus eliminating the chances for uncertain judgements influenced by the human factors as mentioned before.

In this study, we have applied this method to 13 fabrics and the assessment was split in two sessions. In the first session, a batch of seven samples was tested namely knitted – lyocell, cotton and modal micro; woven – modal micro, cotton, modal and lyocell. During the second session the six remaining fabrics i.e. knitted – cotton/lyocell and modal, woven – lyocell micro, wool, polyester and polyamide were tested together with the two reference samples from the first session. There was a gap of one week in between the assessment of the first and the second batch. Later in the analysis, all the samples of the different sessions can be combined as given in the next section.

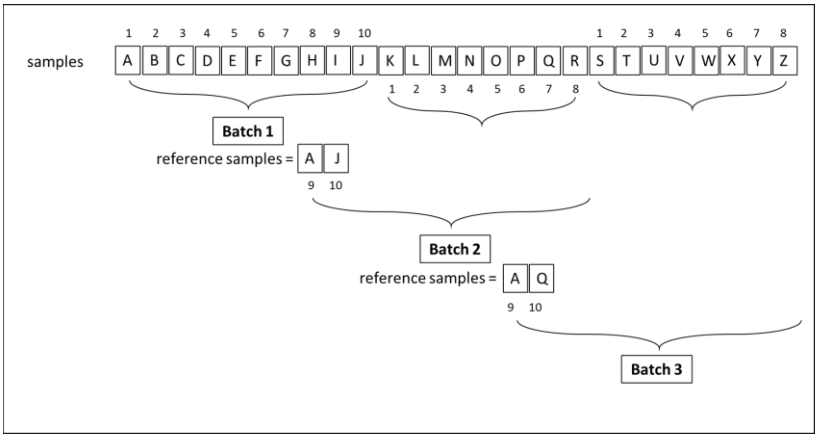

Figure 3-3 Example showing high number of samples i.e. 26 samples (A-Z) are split into batches of maximum 10 samples/batch for human measurement of fabric handle

3.3.5 Analysis method

Since the samples were fragmented in two assessment sessions, data normalization was applied to combine all the data on one new scale. The two reference samples from session 1 (i.e. knitted lyocell and woven modal micro for warmth, knitted lyocell and woven modal for smoothness and knitted lyocell and woven cotton for softness) were assessed in both sessions 1 and 2. We normalize on a scale of 1 to 9 as to bring the value of assessment as much as possible between 0 to 10 and to avoid as much as possible values >10. For each fabric attribute, the average value of the reference samples in session 1 is first determined. We call $\bar{x}_{min}$ for the average of the reference sample with the lowest reading and $\bar{x}_{max}$ is the one of the reference samples with the highest average. Thus we have $1 \leq \bar{x}_{min} \leq \bar{x}_{max} \leq 10$. In session 1, the feature scaling is shown in Equation 2 where x is the original value, x' is the normalized value, a and b are the lowest and highest points in the new scale which are 1 and 9, respectively. For session 2, we obtain the average of the reference samples of session 1 and write them as $\bar{x}_{min,2}$ and $\bar{x}_{max,2}$. The normalized value of session 2 is calculated as shown in Equation 3. If a third session is needed, this approach can be continued as in Equation 4. Further statistical analysis was done on the results, first, a t-test and next, an analysis of variance (ANOVA) with p<0.05. The results given by this method are compared with the relevant studies found in the literatures in which objective evaluation methods are used. This is to verify the findings and to confirm the feasibility of the newly discussed approach.

$$x'_{i,1} = a + \frac{(x_{i,1} - \bar{x}_{min,1})(b-a)}{\bar{x}_{max,1} - \bar{x}_{min,1}} \text{; } i \in \text{sample batch 1; a=1; b=9}$$

(Equation 2)

$$x'_{j,2} = x'_{ref\ min,1} + \frac{(x_{j,2} - \bar{x}_{min,2})(x'_{ref\ max,1} - x'_{ref\ min,1})}{\bar{x}_{max,2} - \bar{x}_{min,2}} \text{; } j \in \text{sample batch 2}$$

(Equation 3)

$$x'_{k,l} = x'_{ref\ min,l-1} + \frac{(x_{k,l} - \bar{x}_{min,l})(x'_{ref\ max,l-1} - x'_{ref\ min,l-1})}{\bar{x}_{max,l} - \bar{x}_{min,l}} \text{; } k \in \text{sample batch } l$$

(Equation 4)

3.4 Results and discussion

3.4.1 Finger sensitivity

The distribution of the panel members' age and origin with their finger sensitivity is presented in Figure 3-4, showing that 54% panel members are from Europe and covers all age groups from 20s to 50s. African panel members consist only 18% and the rest are Asians about 28%. The panel members from Africa are around age of 30s while Asians are distributed from age 20s to below 50. The demographic data is also shown in Table 3-4 below. We verified statistically that the finger sensitivity of the older panel members is lower than the young ones. Through the Pearson's correlation analysis (p=0.02), the relationship of age and the g_{75} score gives R^2=0.32. This means that the effect of the linear model is significant, but as R^2<0.5 the variance is high and is not captured in the linear model based on age, which is to be expected. We can conclude that many factors must play a role in finger sensitivity, but nevertheless the reduction of sensitivity with age is significant.

Table 3-4 Demographic data of the panel members

	age	**origin/ethnicity**	**gender**
number of panel members	20-29 = 9 30-39 = 8 40-49 = 8 50-59 = 3	Europe = 15 Asia = 8 Africa = 5	male = 14 female = 14
total	28	28	28

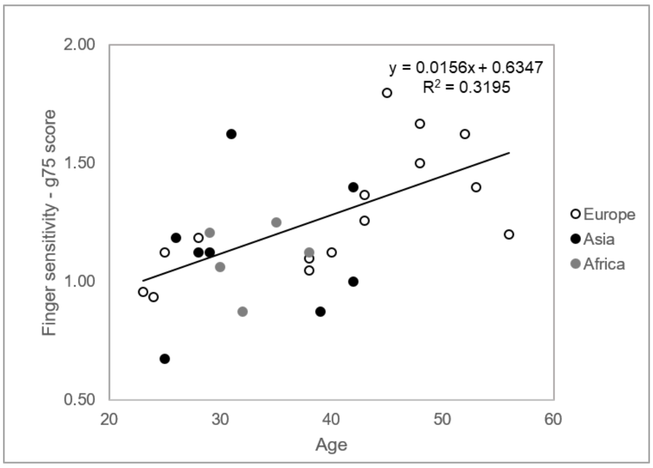

Figure 3-4 Distribution of age and origin versus finger sensitivity of the panel members

In Figure 3-5-left, the boxplots of age vs finger sensitivity show the variance of finger sensitivity for each age group. It seems that the distribution pattern can be further grouped into two groups, i.e. age 20-30 and age 40-50. ANOVA analysis confirms a significant difference between age groups denoted by p=0.001, but the difference only lies for age 20s with 40s and 50s. For origin, the distribution pattern is almost similar for the three groups as shown in the boxplots (Figure 3-5-centre). A resulting p=0.24 shows no statistically significant difference between the sensitivity level of the three groups of origin. Same as origin, males and females also show no significant difference in their sensitivity for the selected group of panel members (p=0.94) (Figure 3-5-right). As the panel members are the selected experts who fall within the range of sensitivity score, it is expected that their demographic aspects do not influence the sensitivity. Hence, the assessment results could not be affected by these factors.

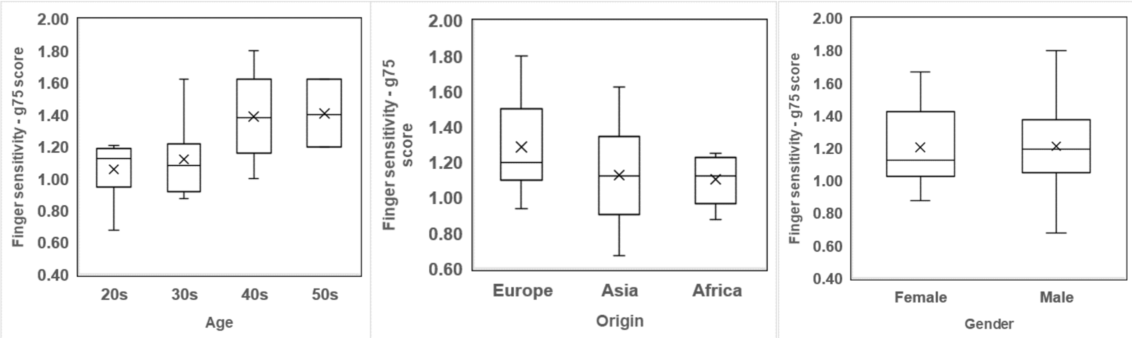

Figure 3-5 Boxplots showing the distribution of panel members' age groups (left), origin (center) and gender (right) vs finger sensitivity

3.4.2 Blind rate experiment

Prior to other analysis, Kendall's Coefficients of Concordance (W) was conducted to determine the consistency of the human assessment results (Kendall, 1970). This analysis is a measure of agreement among quantitative variables i.e. human panel that are assessing a set of objects of interest i.e. handle of the fabrics. Two types of analysis were conducted. First, the consistency for all panel members (inter-panel) in determining the three attributes and secondly, the performance of individual panel members' preference for the evaluated attributes (single panel). It is to note that this type of analysis is designed for rank data. So, first we have to convert the rates into rank to be able to implement the calculation, which based on the rating information is a straightforward conversion. Table 3-5 shows the results for Kendall's W analysis for inter-panel members. We obtained W >0.5 for all three attributes with highly significant results as $p<0.05$. W values range from 0 to 1. The coefficient value close to 1 indicates that the panel members performed consistent assessment amongst themselves. Hence for this data, we can conclude that the consistency of result between all panel members is good. For individual or single panel members, the concordance between the scores they assigned for softness, smoothness and warmth results were analyzed. We found no significant results ($W<0.5$, $p>0.05$). This means no concordance was found, which proves that the panel members were evaluating different properties without being guided by an internal fitness of the fabrics not related to the property under investigation.

Table 3-5 Kendall's consistency test result

	Smoothness	**Softness**	**Warmth**
Kendall's W	0.68	0.89	0.56
p-value	< 0.001	< 0.001	< 0.001

The blind rate method was applied on the materials given in Section 2 – Materials. After normalization as explained in Section 3.3.5, the data from session 1 and 2 can be presented in one scale. The means and standard deviations (SD) of the samples for smoothness and softness are shown in Figure 3-6. Surface of woven and knitted fabrics is known to be different and the thickness of the fabrics also differs between the two groups (i.e., woven fabrics of 0.26-0.43 mm and knitted fabrics of 0.51-0.64 mm). Hence smoothness and softness are separately discussed. Modal fabric was selected as the smoothest and softest knitted fabric. Among the woven fabrics, modal/ modal micro and lyocell/ lyocell micro are clearly smoother than the other fabrics. Modal micro and lyocell micro were found the softest and the hardest woven fabric respectively. The objective measurement with devices such as FTT, TSA and Phabrometer® also indicates modal-based fabrics as the smoothest and softest compared to other regenerated cellulose fabrics (Abu-Rous et al., 2018). Generally, the SD for softness is much lower than smoothness as illustrated by the error bars in the graphs. Nevertheless, the values (maximum SD is 3 for knitted modal– smoothness) can still be regarded as small which shows high agreements on the results between the panel members. In general, wood-based cellulosic fabrics especially modal give smoother and softer handle as shown by higher human scores compared to cotton. This is in line with the findings of previous research (Abu-Rous et al., 2017; Abu-Rous et al., 2018).

In Figure 3-6-right, it can be clearly seen that the fabric construction i.e. woven-knitted, has impacted the softness result where knitted fabrics were generally perceived softer than the woven fabrics. A t-test analysis shows a significant difference between the two fabric constructions ($p<0.001$). Knitted fabrics are known for their bulkiness and airiness, and these would create a soft or fluffy feel when in contact with the skin. In this case, the thickness of knitted fabrics is higher than that of woven fabrics, hence we applied Pearson's correlation analysis which yield R-value = 0.74 with $p=0.001$. This shows a good correlation between the thickness of the fabrics and softness attribute. Figure 3-6-left shows the smoothness results of the fabrics. The smoothness between knitted and woven fabrics is also significantly different but only in case of cellulosic fabrics where woven cellulosic fabrics are significantly smoother ($p=0.006$) than knitted fabrics of same composition. On contrary, non-cellulosic woven fabrics are even rougher than knitted fabrics. These may be attributed to different yarn linear density used for each fabric construction. As finer yarns will lead to smoother fabrics (Kayseri et al., 2012; Luible, 2008), thus we can see that cellulosic fabrics which were constructed with finer yarns (i.e. 10 Tex for woven fabrics and 20 Tex for knitted fabrics) and non-cellulosic woven fabrics made from yarns of 30-40 Tex have different smoothness and roughness feel. A very good correlation with $R=0.84$ ($p<0.001$) was observed between warp yarn linear density and smoothness attribute.

The fabrics of this dataset greatly differ in terms of fabric composition, weave structure and fabric density. Therefore, based on this dataset of 13 fabrics, we cannot conclude which of these parameters led to the change of fabric hand and this is also beyond the scope of this chapter. A Design of Experiment (DoE) could be employed for that purpose, which is a method for systematically planning and conducting experiments by making controlled changes to input variables in order to determine their effect on a given response. It requires a limited number of experiments (combination of input variables) for a maximum amount of information about the responses (Antony, 2003).

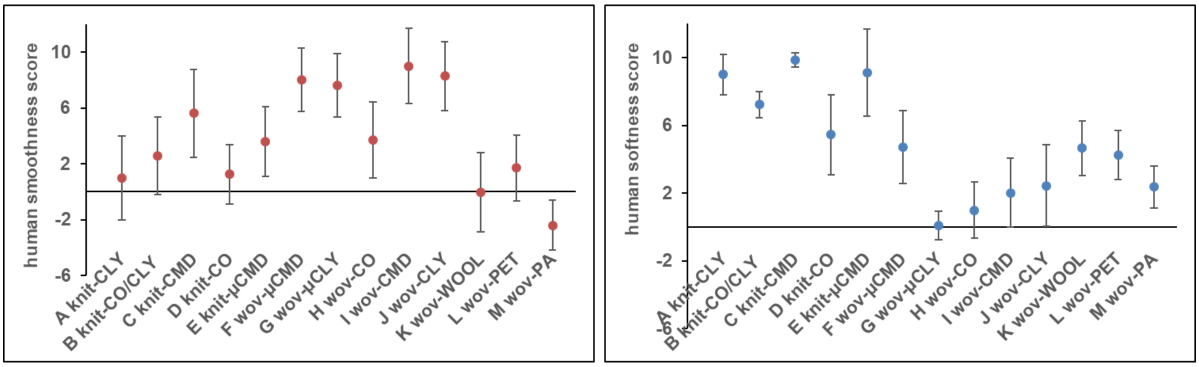

Figure 3-6 Mean scores for smoothness (left) and softness (right) with error bars showing standard deviation (SD)

Figure 3-7-left shows the mean scores for warmth human evaluation given to all fabrics. It seems that woven and knitted fabrics can be segregated based on this attribute. Modal fabric was chosen as the warmest for knitted and polyester for woven, while the coolest for knitted is cotton/lyocell and lyocell micro for woven. Large discrepancies were observed among the panel members which is shown by the error bars. Warmth is measured during the initial contact of the skin onto the fabric and it was evaluated prior the other two attributes. However, the panel members have high disagreement on warmth attribute, which might be due to the small differences on the thermal sensation that the panels were not able to discern. The disagreement among panels was also discussed by previous researchers who also pointed out the same issue on the assessment of warmth (Niedermann & Rossi, 2012; Vasile et al., 2019). Nevertheless, we can still see that the panel members were able to depict the warmth sensation in two groups of knitted and woven fabrics, where knitted fabric were assessed as significantly warmer as compared to woven fabrics (Hu et al., 2006), see Figure 3-7-right. This is confirmed by a t-test statistical method where $p<0.001$. As we look at thickness of the materials, knitted fabrics are thicker than woven fabrics. To some extent, thickness can change the thermal-contact feeling of the tested fabrics which makes thicker fabrics feel warmer (Hes et al., 2001). A good correlation was found between thickness and warmth with $R=0.80$, $p<0.001$. The panel members also indicated that knitted fabrics are rougher than woven cellulosic fabrics. Rougher fabrics have smaller contact interfacial area and more air is entrapped on fabric surface, thus these fabrics gives warmer feeling (Pac, Bueno, Renner, & El Kasmi, 2001) and on the other hand smoother surfaces are perceived as cooler (Vasile, Malengier, De Raeve, & Binti Haji Musa, 2017b; Vivekanadana, Raj, Suffixeenivasan, & Nachane, 2011).

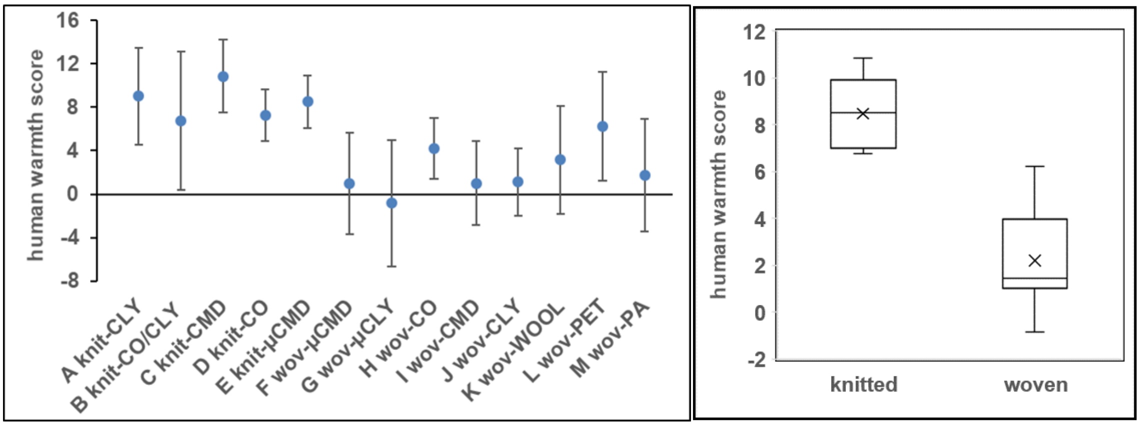

Figure 3-7 Left - mean scores for warmth with error bars showing standard deviation (SD), right -boxplot showing the distribution of human warmth assessment score for knitted and woven fabrics

Since the panel members consist of experienced and inexperienced persons, an ANOVA test was run (significance level alpha=0.05) to identify possible significant differences between the two groups. No significant differences between the two groups were found, probably due to their common background in textiles that makes them familiar with field-specific definitions, terms and testing procedures. Hence, their judgement on the fabric handles was similar. However, the results could have been different if the panels were novices or untrained consumers (Bishop, 1996).

The panel has age varying from 20s to 50s, therefore we analyzed the data to study the differences in assessing the fabrics attributed to age difference. The 28 panel members are grouped by their age where 9 panel members are in age 20s, 8 are 30s, 8 also for 40s and 3 of age 50s. An ANOVA test (alpha=0.05) was applied and the null hypothesis (H_0) was accepted in all cases, meaning that the impact of age on assessment is not statistically significant except smoothness of three fabrics i.e. knitted lyocell, woven cotton and modal fabrics (Table 3-6). It seems that older people find the knitted lyocell fabric smoother than the younger ones and vice-versa for woven cotton and modal as presented in Figure 3-8. As mentioned earlier in the previous section, age of the panel members can be grouped into two i.e. 20s-30s and 40s-50s, based on their finger sensitivity. Hence, we analyze the smoothness results of these three fabrics based on the two groups, as visualized in Figure 3-9. It is found that only woven cotton fabrics have significant difference between the two groups of age. Nevertheless, this single exception out of all other cases should not be given too much weight as it could randomly appear through the statistics, as we might find also if we test nonsensical parameters such as height or weight of the panel members vs their subjective judgement.

Spatial acuity of touch depreciates noticeably by age as reported by many researchers.(Gerhardt et al., 2009; Wickremaratchi & Llewelyn, 2006; Zhu et al., 2011) As we grow older, our sensitivity reduced, likewise for the touch perception on the fabrics. However, this factor could be different for each individual as in our case. As mentioned earlier, the panel members in this study were carefully selected having good range of skin sensitivity after being screened with

JVP Domes. Hence, it is expected that the panel members' age would not give much influence to the touch, for this particular study.

Table 3-6 Results for ANOVA analysis showing p-values where $p<0.05$ indicates the rejection of H_0 hypothesis (H_0= assumes the means of the samples are the same among the groups studied)

Fabric ID	p-value for age groups – 20s, 30s, 40s, 50s			p-value for origin – Europe, Asia, Africa		
	smoothness	softness	warmth	smoothness	softness	warmth
A-knit-CLY	0.02*	0.22	0.36	0.18	0.17	0.01*
B-knit-CO/CLY	0.79	0.71	0.46	0.85	0.15	0.86
C-knit-CMD	0.06	0.94	0.69	0.02*	0.16	0.95
D-knit-CO	0.28	0.86	0.53	0.66	0.93	0.10
E-knit-µCMD	0.50	0.70	0.14	0.20	0.41	0.12
F-wov-µCMD	0.47	0.36	0.86	0.87	0.28	0.92
G-wov-µCLY	0.10	0.64	0.49	0.49	0.55	0.01*
H-wov-CO	0.00*	0.27	0.84	0.15	0.08	0.78
I-wov-CMD	0.00*	0.60	0.68	0.10	0.17	0.06
J-wov-CLY	0.08	0.95	0.78	0.73	0.97	0.16
K-wov-WOOL	0.51	0.20	0.30	0.70	0.67	0.60
L-wov-PET	0.69	0.11	0.56	0.57	0.33	0.97
M-wov-PA	0.63	0.67	0.24	0.95	0.26	0.38

*significant difference between sample, p-value<0.05

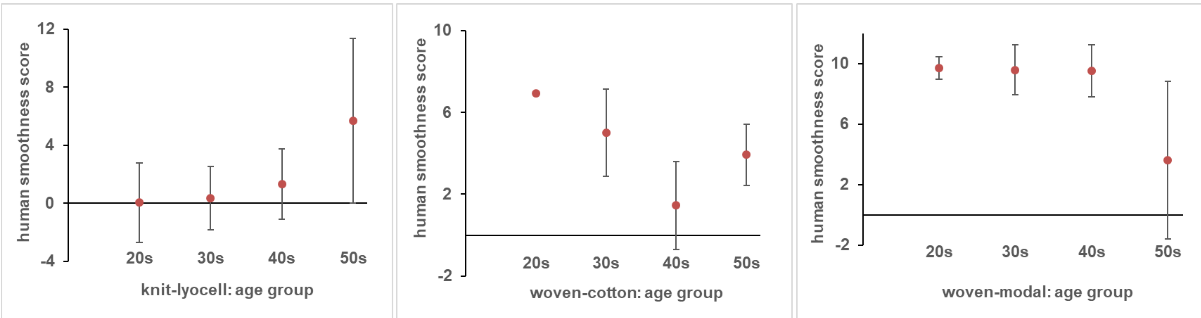

Figure 3-8 Mean scores for smoothness vs age of the panel members for knitted lyocell (left), woven cotton (middle) and woven modal (right)

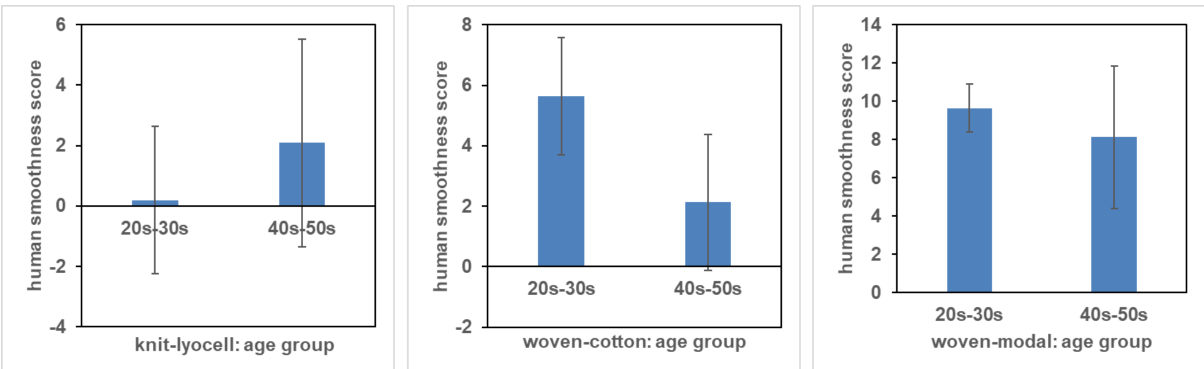

Figure 3-9 Results for human smoothness score in two age groups (20s-30s and 40s-50s) for knitted lyocell (left), woven cotton (middle) and woven modal (right)

An ANOVA analysis was applied on the data obtained from panel consisting of 15 Europeans, 8 Asians and 5 Africans to identify assessment differences due to origin. Similarly, we found that the origin of the panel members does not influence their judgement of fabrics handle with exception of three cases i.e. smoothness for knitted modal, and warmth for knitted lyocell and woven lyocell micro (p-value<0.05 as tabulated in Table 3-6). The graphs in Figure 3-10 show that Africans feel the knitted lyocell fabric as cooler but warmer for woven lyocell micro compared to Europeans and Asians. For knitted modal fabric, Asians found it rougher than Europeans, and Africans found it as the smoothest. Again, these exceptions are minor cases which should not be given much emphasis. The results of finger sensitivity showed no significant differences between the panel members due to their origins, as reported earlier in the previous sub-section. Similarly, we found no significant differences between the fabric handle assessment of males and females panel members ($p>0.05$). Since we already screened the finger sensitivity of the panel members and retained only those within a certain range, it seems that the disagreements between the panel members due to demographic criteria i.e. age, gender, origin can be overruled. We also analyse the relationship between the finger sensitivity and subjective assessment score. The results showed no correlation for all three attributes.

Although some previous research found that there are apparently culturally based differences in handle assessment, those are mainly for preferences on good hand fabric. For instance, Japanese panel members prefer stiffer fabrics, in contrast with Australian, New Zealand and Indians who preferred a relatively lower stiffness for a lightweight summer materials (De Boos & Tester, 2005; Dhingra, Liu, & Postle, 1989). This kind of cultural bias was not encountered in our study.

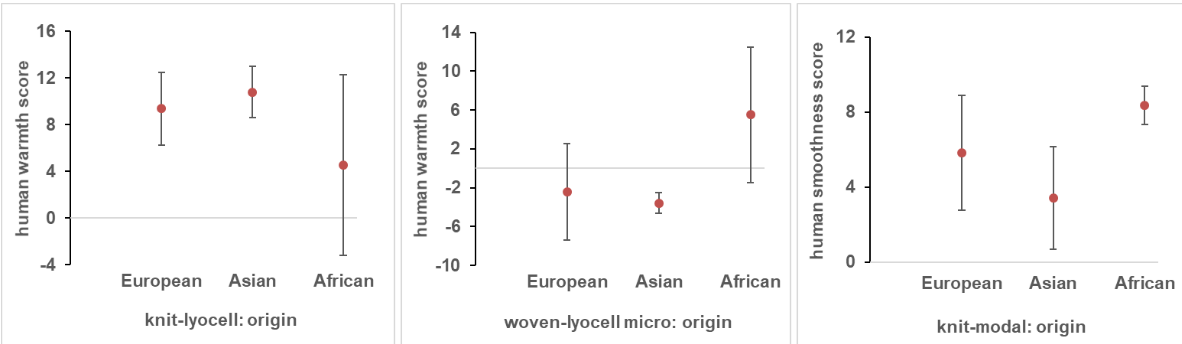

Figure 3-10 Warmth scores vs origin of the panel members for knitted lyocell (left), woven lyocell micro (middle) and smoothness scores vs origin for knitted modal (right)

3.5 Conclusion

Fabric hand assessment prominently relies on the feel of humans. Generally, the size of fabric sets impacts the precision of the results where it decreases with increasing number of samples. This is due to the human factors in which they are prone to fatigue and loss of focus when assessing a large sample sets, in addition to a long testing duration. Considering the importance of handle assessment and the lack of guidelines that assist assessment of large sample sets, this study suggests a method to test a large set of fabrics in which the samples are split in several sessions, with 10 samples at most for each session. To overcome possible disagreements between the panel members as results of their different age, gender and origin, a selection method is proposed based on their finger sensitivity. The method to select the panel members, link the results obtained in different sessions and normalize the data are discussed in this paper.

The proposed method was implemented on 13 fabrics from a typical range of apparel clothing fabrics. Three fabric sensorial attributes (i.e. smoothness, softness and warmth) were assessed in two sessions by a panel consisting of 28 blindfolded members. Good agreement was found between the panel members for fabric smoothness and softness. However, the panel judged the warmth of the fabrics differently, probably due to small, difficult to discriminate differences between the samples and their personal preferences. Nevertheless, the panels clearly differentiated knitted and woven fabrics according to their warmth.

We found no significant differences between the assessments due to gender, origin or age-based difference. That can be attributed to the background in textiles engineering of all panel members and their selection criteria was based on similar finger sensitivity. The findings of this study are in agreement with previous studies where well-established assessment methods were applied and suggest that the proposed method can be applied to assess large sets of fabrics. As a limitation, the fabrics need to have comparable thickness, weight, texture etc. Otherwise, the rating scale of 1 to 10 would be too limited to grasp the full range of fabrics. In other words, the reference samples should not grow too distinct.

Through the present technique using split sample batches, large-size set of fabrics can be assessed without jeopardizing the focus of the panels. This triggers future possibilities for inter-laboratory assessment after selecting the reference fabrics to be used across institutions. By this means, diversified type of fabrics can be evaluated by larger panels located worldwide, thus the results will be more meaningful. We used this technique for the construction of new deterministic models for fabric handle in Chapter 5.

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4

Predictions of fabric touch sensations

Forecasting is the art of saying what will happen, and then explaining why it didn't!

This chapter presents the literature on the prediction method for fabric touch sensations. Three types of models are discussed and analysed i.e. statistical, artificial intelligence and biomechanical. The author also introduced a biomechanical model which is an extension from the previous work of another author. This model is still at its early stage.

4.1 Introduction

Since the discovery of Binns and Peirce (Binns, 1926a, 1934; Peirce, 1930b) with regards to the measurement of some human sensory perceptions and fabric properties, researchers have continuously quantified these aspects. There are also many efforts to correlate both i.e. sensory perception or human assessment and fabric properties. Normally, based on the limited test sets used in the study, a prediction model is developed in order to be able to estimate the property for other materials other than the one used to generate the prediction model. The usefulness of a fabric handle assessment method, either objective or subjective, relies upon their ability to predict the touch sensation of a fabric. The closer the prediction to the human perception, the better the method is. Hence, the most important criteria to develop a method or technique for handle evaluation is the capability to mimic the results of human touch perception, other than the technicality and practicality aspects of the method itself. Prediction of fabric touch sensations is made possible through several methods i.e. statistical modelling, artificial intelligence and quite recently, biomechanical models. The methods will be elaborated next.

4.2 Prediction methods

4.2.1 Statistical modelling

Statistical modelling, also referred as mathematical and numerical modelling, are widely used to predict fabric touch. This modelling technique requires a rigorous statistical analysis implemented on a large amount of numerical data in order to develop a good prediction model in which the forecasted value of independent variable would be estimated through a build model equation.

There are several modelling approaches available. In practice, stepwise, multiple and linear regression are the most common methods. In the development of KES-FB system, statistical models were developed to correlate the subjective assessment of human and the measurement of fabric properties (Kawabata, 1980; Kawabata & Niwa, 1989). Normally, other fabric handle devices i.e. ring (extraction method) and QIHES-F were also based on statistical analysis data to make prediction on the fabrics handle (El Mogahzy et al., 2005; Pan, 2007; Pan, Yen, Zhao, & Yang, 1988; Sun et al., 2018). However, no explicit models were disclosed by the manufacturer for SiroFAST and FTT devices.

In a research to simulate psychological sensory perceptions of clothing comfort conducted on 22 professional athletes in a series of wear-trial of four garments, a linear model was obtained (Wong, Li, & Yeung, 2002). Subjective ratings of 10 sensations i.e. clammy, clingy, sticky, damp, heavy, prickly, scratchy, fit, breathable and thermal were recorded and factor analysis was first carried out to cluster the factors into three and five factor models. They found a good linear relationship with the models and the actual comfort score rated by the assessors.

Regression model was used to account for the total tactile comfort of a human which was expressed in two ways i.e. mechanical properties of fabrics which were measured by KES-FB and sensory properties assessed by expert panel (Sztandera, 2008; Sztandera, 2009; Sztandera, Cardello, Winterhalter, & Schutz, 2013). In this context, the total tactile comfort is the human perception score measured using the Comfort Affective Labeled Magnitude (CALM) scale. The scale ranges from –100 to 100 where a score of –100 represents the greatest imaginable discomfort, and a 100 represents the greatest imaginable comfort. They applied stepwise regression to reduce the parameters in the model. Based on the goodness-of-fit of the regression model, they found that the sensory properties were better correlated to the total tactile comfort, in comparison with the fabric mechanical properties. Nevertheless, both methods provided reasonable ways for tactile fabrics prediction. Regression model was also used by other researchers to quantify fabric handle or comfort of terry (Krasteva, 2015) and mattress ticking fabrics (Vasile et al., 2019) based on subjective and objective evaluation. In some cases, the developed models were utilised for the measurement of fabric handle using devices such as QIHES-F and Phabrometer® (Pan et al., 1988; Sun et al., 2018). The models developed within Touché project were intended to be use in a later research (Vasile et al., 2019), in which this thesis reports the continuation of the project findings. The work on improvement of the models will be reported in the next chapter of this thesis.

4.2.2 Artificial intelligence

Artificial intelligence (AI) is a buzz word nowadays which is used to describe machines that are made to be able to ‘think’ or mimic the process associated with human minds such as learning and problem solving. In the context of fabric handle assessment, the use of AI involves the prediction of touch perception of fabrics. To be able to predict the handle as what humans feel, AI machines should be furnished with inputs that can be learned by the machine which will be included in its memory.

Within AI, neural network (commonly abbreviated as ANN for artificial neural network) is the most explored method for fabric handle prediction. ANN was defined as ‘computational networks which attempt to simulate, in a gross manner, the networks of nerve cells (neurons) of the biological (human and animal) central nervous system’ (Graupe, 2007). It is also known as an adaptive statistical model, taking a brain structure as an analogy, as ANN is able to learn to estimate the parameters of some populations using a small number of exemplars at a time. Figure 4-1 shows a multilayer ANN structure that is typically applied among other structures available within ANN. The basic building block of ANN is the simulated neuron. Each layer consists of neurons which receive signal from the neurons of the previous layer. Through synaptic weights that multiple the signals, the inputs are summed up and passed through a transfer function which converts them into a fixed range of values. This process happens in the hidden layers as the neurons are transmitted from one layer to the next layer to carry the output of the previous one. There can be many hidden layers which means many levels of non-linearity and many interactions can happen within the structure. The output is produced at the output node. In case the output does not match with the desired output, an error signal is generated. By adjusting the synaptic weights using a suitable training algorithm, these signals are then reduced, thus the desired output is achieved (El-Ghezal Jeguirim et al., 2011).

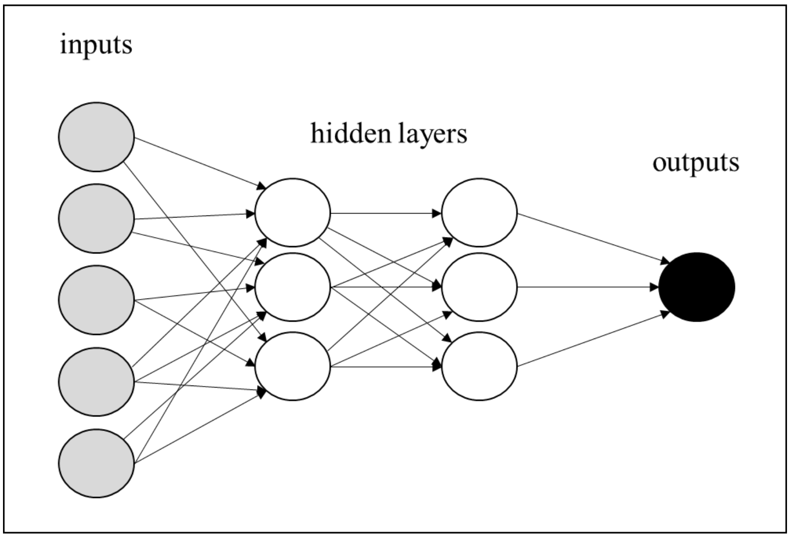

Figure 4-1 A typical multilayer structure of ANN

ANN takes previously solved examples to looks for patterns. Then, it learns the patterns, and develops the ability to correctly classify new patterns i.e. provide forecasts or predictions. The inputs, in the form of human perception of various fabrics are needed, as well as the physical and mechanical properties of them, for the machine to learn the pattern made by such inputs. From the patterns that it recognized, the machine is capable to correctly predict the handle for other fabrics, provided that their properties are within the established patterns that the machine has learnt.

The use of back-propagation ANN in predicting the handles of some fabrics was first tried by researchers to measure the handle of worsted fabric (Youssefi & Faez, 1999). Their network was trained with different layer nodes for 16 training sets and the training was stopped when the sum-squared error (SSE) became less than 0.001. They obtained a good prediction for the model with the actual value. The same conclusion was obtained by another group of researchers when they measured human psychological perception with the back-propagation ANN (Hui, Lau, Ng, & Chan, 2004). Other researcher used ANN to predict the comfort of car seat fabrics and compared with a statistical model (Kolich, Seal, & Taboun, 2004). While both models could be used to adequately predict subjective perceptions of comfort, they found that the neural network was deemed superior due to higher R^2 values and lower average error values.

ANN is also use in hybrid form with genetic algorithm techniques. An attempt was made for a case of reverse engineering in which the objective is to identify the material properties for a given level of tactile comfort (Karthikeyan & Sztandera, 2010). Since training the ANNs with one input and 17 outputs of fabric properties is not suitable, an ANN-genetic algorithm hybrid engine was proposed. The trained ANN serves as the objective function to evaluate the property set while the solution set is generated by genetic algorithm. The result was promising as the hybrid system is capable of identifying the set of mechanical properties that gives a required amount of tactile comfort.

Another method derived from human intelligence insights is known as fuzzy logic (FL). This method was proposed in 1965 to simulate the perception and judgement of human brain on the basis of fuzzy information and rules (Zadeh, 1965). Rather than the Boolean logic of 'true or false' which was the basis for the development of computer, FL computes based on a 'degree of truth'. It uses 'if-then' rules and logical operators to compute the relationship among the variables in a qualitative manner, hence the fuzzy model is regarded as a logical model (Babuska, 2003).

Figure 4-2 shows a fuzzy simulation process. In the beginning, all the input data variables need to be characterized into words in fuzzy form. This is called as fuzzification process. By giving a set of rules to the variables, an inference process is executed in which the relationship between input and output are evaluated. Then, the outcome from the inference is combined and defuzzified to give the crisp outputs.

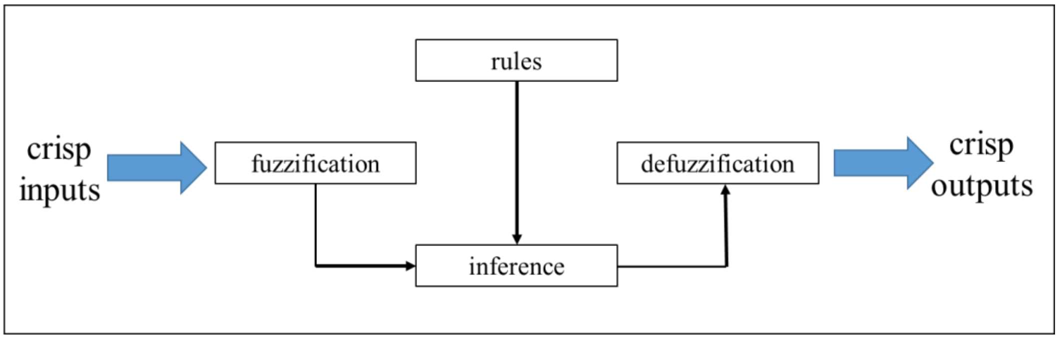

Figure 4-2 Fuzzy simulation process

A study to determine the overall comfort of fabrics through a simulation of an overall psychological process of judgement on clothing comfort used FL method (Wong, 2002; Wong, Li, Yeung, & Lee, 2003). The FL examines the interrelationships among various sensory perceptions and their contributions to the psychological judgement towards the overall clothing comfort status. More than 20 rules were developed and applied to the simulation. The predicted comfort scores were compared with the actual comfort rating. Good agreement has been observed which concludes that FL method is capable of predicting the comfort through linguistic reasoning in fuzzy format.

An attempt to combine FL and ANN method was reported in a study to measure total handle of knitted fabrics (Park et al., 2000). The inputs were first transformed into fuzzy values and after fuzzification, the fabrics with unknown mechanical properties were evaluated as inputs elements for ANN. The results showed that the overall hand values were associated with the subjective assessment, and hence proved the predictability of the models from the combined methods.

The comparison between FL, ANN and linear statistical methods was studied by a group of researchers (Wong, Li, & Yeng, 2004; Wong, Li, & Yeung, 2003). They developed hybrid models in four stages of building the theoretical model for clothing comfort prediction. The first to third stage used the same procedures for the process of abstracting the physical and subjective perception rating into physical and sensory factors, and also prediction of sensory factor, but the overall comfort perception was performed in three different ways i.e. FL, ANN and linear models. The hybrid model with FL gave the best prediction of the total comfort, followed by the ANN models. However, linear hybrid models performed poorly which indicates that the fuzziness of subjective judgements and dynamic learning of the ANN simulation were able to capture more information on human perception than the linear models.

4.2.3 Biomechanical modelling

Apart from the prediction of fabric handle through statistics, ANN, FL or hybrid formations of the methods, in recent years, researchers started to look into the potential of biomechanical modelling. This kind of modelling is inclined to the idealized system of measuring hand of textiles in which the model of tactile related sensory organ i.e. skin was developed to simulate a real touch behaviour. For that, the understanding on how the sensory system works is crucial.

The conceptual plan was to create a fingertip skin section that contains all receptors involved in tactile feel (Ciesielska-Wrobel et al., 2014; Ciesielska-Wrobel & Van Langenhove, 2012). The understanding of the principle of mechanical deformation of tissues within the skin structure could advance the prediction of the tactile sensory system responses. Thus, this idea sets a good premise to be explored and expanded. Since this field involves the application of mechanical principles to biological system, i.e. human organs, the kind of models generated are referred as biomechanical model.

Skin has been modelled in many ways in other field of study, mainly related to medical applications. However, for the purpose of haptic sensation and tactile prediction of fabrics, there is a scarcity of information. The currently available model shows the skin mechanics using a finite element method with 3D cross sections of the fingertip skin (Ciesielska-Wrobel et al., 2014). The models were generated in a solid cubic shape to represent the part of the skin involved in the touch behaviour (see Figure 4-3 and Figure 4-4). Several mechanical parameters were applied to the models i.e. Young modulus: 136 kPa for the epidermis, 80 kPa for the dermis, and 34 kPa for the hypodermis, and a Poisson’s ratio of 0.48 for all skin layers. 1 N loading was uniformly distributed on the skin surface. These models were tested and they are shown to be capable of replicating the changes imposed by the given pressure in the simulation.

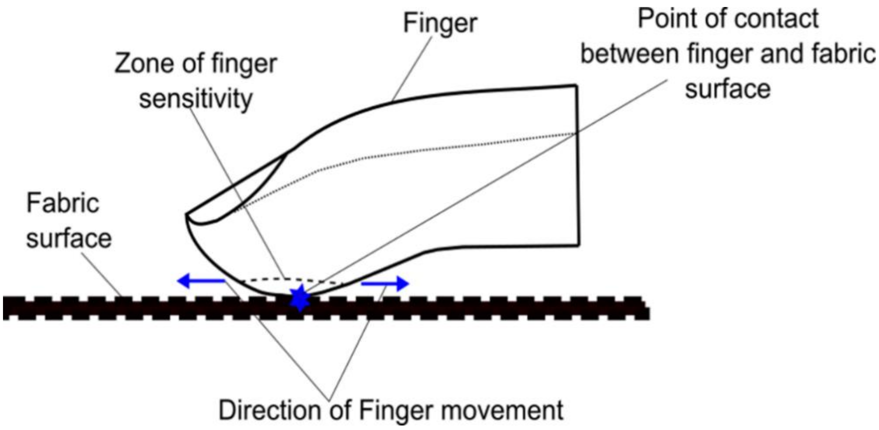

Figure 4-3 Schematic diagram showing the touch behaviour of a human finger

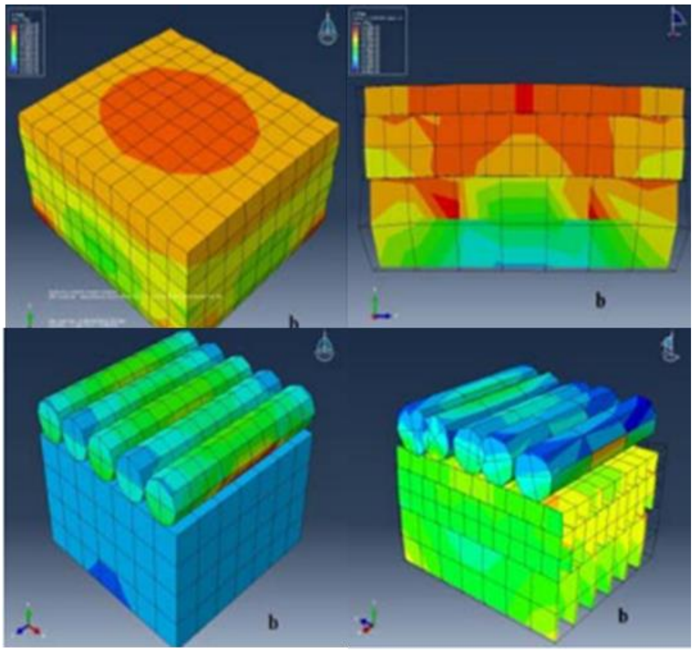

Figure 4-4 Geometry of the finite element models presenting fingertip skin sections showing deformation on the skin (Ciesielska-Wrobel et al., 2014)

The author of this thesis and her team made an attempt to expand this approach. The geometry of the finger is fine-tuned to mimic the real human finger (see Figure 4-5). However, fingerprint lines, bones, nails, and mechanoreceptors are still not included in the model. The models were constructed as an isotropic elastic material. Contact algorithms are added, and static and sliding friction are considered. The mesh utilized eight-node, hexahedral, linear, reduced integration, hourglass control (C3D8R) for finger, and a two-node linear beam in space (B31) for fabric model. Boundary condition imposed the displacement in x-direction. Figure 4-6 shows the simulation of textile-skin during touch assessment showing deformation on the skin, as well as the textile substrate.

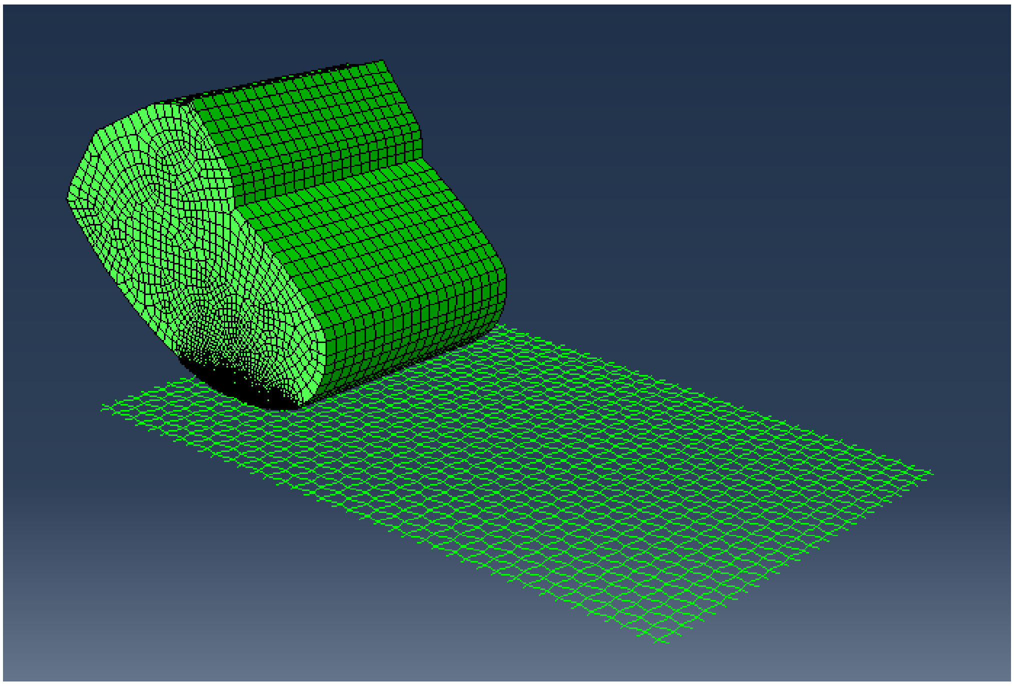

Figure 4-5 New proposed finger geometry and a substrate

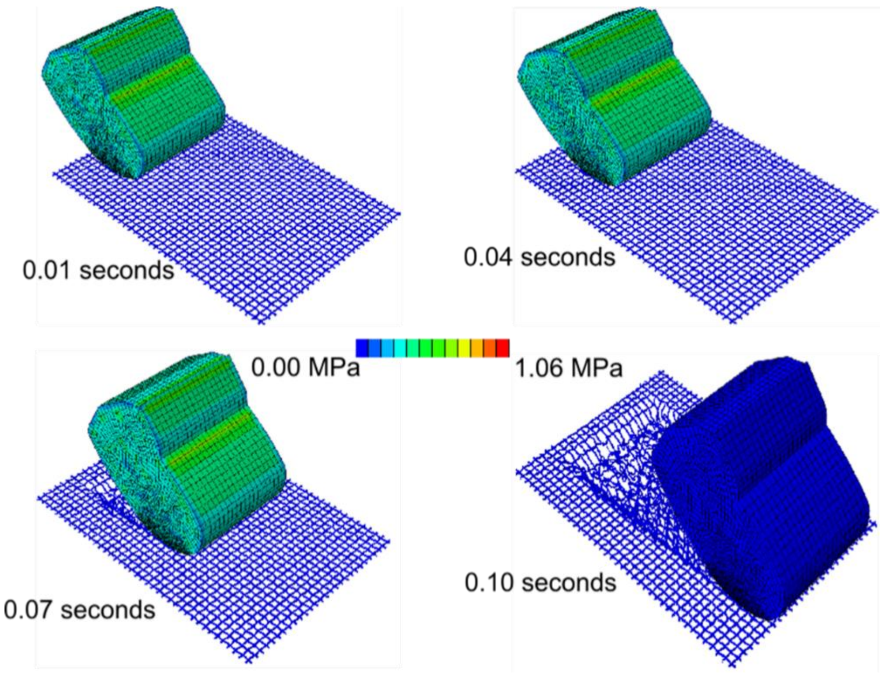

Figure 4-6 Textile-skin contact simulation

As this field is still in the initial stage, many angles can be discovered and explored. Based on haptic feedback literature, it was found that touch sensation in the fingertip depends on the full finger structure, so the entire fingers should be modelled. An improvement on geometry with the inclusion of several layers resembling the skin would hence be a way forward, but a high complexity of the models is then expected and would reduce the efficiency.

There is no doubt that this kind of model offers a huge potential for the prediction of handle perception of the fabrics. A high precision model with a possibility of mimicking skin sense organ offers immediate prediction at high accuracy and credibility. Many unknowns remain still, however at this stage. Knowing the conditions at the mechanoreceptors as these models compute does not give insight yet in the actual signals send to the brain. Psychological research also indicates that the brain will react depending on the interplay between signals, e.g. edge detection, slip and thermal sensation. A correct biomechanical model does not answer these questions, and a model to select signals would be required. Human panel testing would be needed to guide these models. Another open question is how to translate fabric properties to the fabric layer. At the moment, a plate is used, but this is a poor substitute for an actual fabric. A realistic construction of a virtual fabric is very difficult. However, once such a model is present, it would be possible to test independent effect of small structure changes on a simplified fabric, to further increase the understanding on the skin-interaction. This would be a reachable goal of these models.

4.3 Analysis of the methods

Three types of prediction models i.e. statistical, artificial intelligence and biomechanical were presented earlier in this chapter. Some refer to statistical models as the traditional method, as it has deep roots in the field, in comparison with other methods. Artificial intelligence is not new but still has to develop much more. On the other hand, biomechanical model is still green, hence it requires much works to realize the conceptual idea.

Statistical models which are normally obtained through regression, are a widely used method to make prediction as reported in section 4.2.1. Owing to its capability to apply data reduction and also a clear structure that the model provides i.e. explicit relationship and weight of independent and dependent variables, this type of model is easy to understand and interpret. ANN which is one type of AI is a fast and flexible prediction tool that has self-learning ability. However, the functions and interrelationships of the variables are unknown. This is a major drawback of an ANN model as it acts rather like a “black box” without revealing any physical information about the mechanics of the process. ANN also requires correctly annotated datasets, which in the textile research is not common. In order to do ANN, a larger dataset is required. In this thesis, a method to achieve this is given as in Chapter 3, so that ANN would be applicable on our data in the future. For this reason, our data is freely available as on open dataset at github.ugent.be/UGentTextile/FTTAnalysisOpen.

Another AI method, FL has reasoning capability. Since it is in linguistic form, the models are relatively easier to interpret and it is also able to produce linguistic solution. However, it has lack of weighing and data reduction capability and also self-learning capability, same like the statistical model.

The biomechanical model is independent from laboratory based experiments as it does not build an objective evaluation on fabrics or subjective assessment on humans. However, an ability to understand the human sensory organ is crucial since the closer the model is to the reality, the better the prediction will be. Moreover, though sensory activation can be obtained, how this translates in the human brain will still require modelling. This method still needs a long way to be close to the reality as conceptually intended. Although the approach is new, it has a great potential and promising future. Table 4-1 summarized the advantages and disadvantages of the discussed models in a concise format.

Table 4-1 Advantages and disadvantages of the prediction models

	Statistical model	ANN	FL	Biomechanical
Advantage	- provides data reduction - explicit relationship and weight of independent and dependent variables - easy to understand and interpret	- self-learning capability	- reasoning capability - knowledge based system in linguistic form, hence easy to understand and interpret the outputs	- independent of laboratory test - it models the actual phenomena of textile-skin relationship, hence the model is close to reality
Disadvantage	- unable to self-learn - unable to do fuzzy reasoning	- unknown functions and interrelationships of the variables - difficult to interpret - large annotated datasets needed	- unable to self-learn - large annotated datasets needed	- no established model yet - high effort needed to realize the model - interpretation of finger sensation into brain response needed - realistic construction of a virtual fabric is very difficult

4.4 Conclusion

From the finding of various research presented in the earlier section of this chapter, it shows that all the models have their own strengths and capabilities. They are also found to adequately predict the intended tactile or comfort properties with high precision to the actual phenomena within academic papers. In order to come to the understanding of the complex phenomena behind the perception of tactile comfort, the connection between the properties of the fabrics and their derived haptic sensations should be discovered. Therefore, in this regard, statistical modelling will be used by the author in the next chapter, since it offers an explicit detail on the variables, as intended for this study, and can be applied already when small sample sets are used. As human panel testing is expensive, few institutes have large annotated datasets.

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5

Fabric Touch Tester – improvement on predictive comfort models

The only way to do great work is to love what you do.

Steve Jobs

This chapter further develops the comfort models of FTT. A comprehensive experimental procedure was executed in order to evaluate the components of fabrics which dominantly affect the tactile comfort. A comparative analysis suggests a new refinement of the current model. Therefore, new models are reported and discussed in this chapter. Validation of the models is included as a test run.

5.1 Introduction

FTT predicted three comfort indices i.e. smoothness, softness and warmth. These indices were generated by the manufacturer through a series of statistical analysis where human assessment was the fundamental basis of the calculation. In Chapter 2, the singular index of FTT was examined. Here, the focus will be on the performance of the predictive models. Therefore, experiments were run on samples for subjective and objective tests and the relationship between both assessment was obtained. Analysis will be made to compare the reconstructed statistical models that were described in Chapter 2 with the result obtained for the samples set tested.

During the Touché project which was mentioned previously in Chapter 2, the FTT was tested and compared with KES-FB, TSA and limited panel testing. Several published results conclude the advantage and drawbacks of FTT to measure the fabric handle of selected fabrics i.e. protective clothing (Vasile et al., 2016), various cellulosic fabrics (Abu-Rous, 2016; Abu-Rous, Liftinger, & Innerlohinger, 2017; Abu-Rous et al., 2018), mattress-ticking fabrics (Vasile et al., 2019), and fabrics treated with different type of finishes (Binti Haji Musa, Malengier, Vasile, & Van Langenhove, 2018a; Vasile et al., 2017a). These studies reported on some limited spectrum of usage of FTT. For example, some researchers focused on FTT fabric indices only, another group investigated on smoothness or softness measurement only, and one made comparison between FTT comfort prediction with other instruments. From the previous works, FTT is found to be able to discriminate fabrics with similar or very small differences of weight and thickness (Vasile et al., 2016). A comparison with human assessment mostly agreed on the softest and smoothest range, but not in the rankings for harder and rougher fabrics (Abu-Rous, Liftinger, & Innerlohinger, 2017; Abu-Rous et al., 2018). FTT is also capable to differentiate the effect of softener and dye on its comfort indices and also differences in production setting i.e. mass, concentration for treatment solution, and fibre composition for different fabrics made from the yarn of different spinning systems (Binti Haji Musa, Malengier, Vasile, & Van Langenhove, 2018a; Vasile et al., 2017b). For the assessment with mattress ticking fabrics, the fabric indices of FTT were found to have strong correlations with several tactile properties assessed by panels i.e. softness, smoothness and flexibility, but not warmth (Vasile et al., 2019). It seems that the full warmth feeling cannot be grasped by the FTT fabric parameters.

Since the function of FTT is to measure the fabric properties and compute the comfort properties of the fabrics based on the measured indices, a thorough study which includes the measurement of FTT fabric properties, variation of the FTT fabric indices given by the differences in the tested fabrics, interaction between the indices, and also the validation of the FTT comfort models, needs to be carried out. Some parts of the research have been conducted as cited above and also included in Chapter 2. Therefore, in this chapter, a detailed study about FTT is conducted focusing on the investigation on the relation of the FTT predictive model and the validity of the models to estimate the handle of the fabrics.

5.2 Experimental samples

As the models were generated based on assessment of various fabrics, the diversity of the fabric is an important aspect in order to regain the original composition of the models. Hence, this work utilizes 13 non-homogenous fabrics consisting of cellulosic, wool, polyester and polyamide with woven and knitted structures. The mass per unit area of the fabrics (EN 12127:1997) varied between 122 – 157 g/m^2 and their thickness from 0.26 to 0.66 mm (EN ISO 5084:1996). Table 3-2 shows specifications of the fabrics. The selected fabrics are in the typical range of apparel clothing fabrics. These fabrics are the same set as previously reported in Chapter 2 (section 2.6.3) and Chapter 3 (section 3.2).

Table 5-1 Specification of the materials

Fibre composition	**Fabric ID**	**Mass per unit area (SD), g/m^2**	**Yarn linear density (Tex)**		**Fabric density (warp/ wale x weft/ course per cm)**	**Thickness (SD), mm**	**Fabric construction and finishes**
			Warp/ wale	**Weft/ course**			
100% Lenzing™ Lyocell	A-knit-CLY	125 (2.60)	20/1	20/1	13x16	0.60 (0.02)	Knitted -Single jersey Washed on frame, no additional treatment.
50/50% cotton/Lenzing™ Lyocell	B-knit-CO/CLY	152 (0.88)	20/1	20/1	14x20	0.64 (0.02)	
100% Lenzing™ Modal	C-knit-CMD	140 (0.63)	20/1	20/1	14x20	0.51 (0.01)	
100% cotton	D-knit-CO	157 (2.21)	20/1	20/1	15x20	0.66 (0.01)	
100% Lenzing™ Modal Micro	E-knit-µCMD	155 (1.63)	21/1	21/1	15x20	0.57 (0.02)	
100% Lenzing ™ Modal Micro	F-wov-µCMD	134 (0.63)	10/1	10/1	78x51	0.27 (0.00)	Woven - Satin 5/3 Desized and washed, no additional treatment
100% Lenzing™ Lyocell Micro	G-wov-µCLY	136 (0.61)	10/1	10/1	77x51	0.27 (0.02)	
100% cotton	H-wov-CO	135 (0.84)	10/1	10/1	75x58	0.32 (0.02)	
100% Lenzing™ Modal	I-wov-CMD	138 (0.46)	10/2	10/2	78x53	0.27 (0.01)	
100% Lenzing™ Lyocell	J-wov-CLY	131 (0.35)	10/1	10/1	77x52	0.26 (0.01)	
*100% wool	K-wov-WOOL	122 (1.16)	30/2	30/2	21x18	0.30 (0.01)	Woven – Plain weave, no additional treatment
*100% polyester	L-wov-PET	132 (0.43)	34/2	24/1	25x20	0.34 (0.01)	
*100% polyamide	M-wov-PA	150 (1.62)	44/2	22/1	22x20	0.43 (0.02)	

*adjacent fabrics used in testing of colour fastness (the specification are controlled according to ISO 105-F01/F03/F04:2001 standards.

5.3 Methodology

5.3.1 Objective measurement of FTT

All 13 fabrics were tested by the FTT according to the method explained in Chapter 2. Each fabric was cut in an L-shaped and placed on the lower plate of the FTT instrument with the two arms of the L-shaped positioned on adjacent platforms within the device. Prior to testing, the upper plate was controlled at 10°C higher than the lower plate as to mimic the temperature difference between skin and textiles. When the test starts, the upper plate moves gradually downward and touches the fabric on the lower plate. The fabric is brought further downward by both plates and in several seconds, it reaches the lowest position after which it goes back to the initial position. During the upward and downward movement, the fabric compression, bending, thermal and surface properties (i.e., friction and roughness) are measured. The measured properties yield 13 different FTT fabric indices and next, the primary (i.e., smoothness, softness, warmth) as well as the global comfort indices (i.e., total hand and total touch) are computed by the FTT software which are linear combinations of the FTT fabric indices (J. Hu, 2006). For each fabric, 20 specimens were tested, 10 for outside and another 10 for inside. Each time, both fabric wale (a) and course (e) direction were simultaneously measured. The 13 indices measured by FTT were listed earlier in Chapter 2. As there is no standard yet, the test is done by following the guidelines provided by the manufacturer and also based on author's own experience, as already published in a paper (Binti Haji Musa, Malengier, Vasile, & Van Langenhove, 2018b).

5.3.2 Subjective measurement by human panel

It is assumed that the variation in the materials e.g. fibre composition, thickness and fineness, will lead to fabrics with different smoothness, softness and warmth. These fabric attributes are the most common tactile sensations felt by humans. Hence, the attributes were assessed by human panels through the newly introduced blind-rate method (description in Chapter 3). The method was applied double-blind, meaning that the supervisor who conducts the test and the panel members do not know the details about the fabrics. For this assessment, all 13 fabrics were considered. The human panel consisted of 28 individuals (i.e. textile engineering postgraduate students, researchers or technical staff), 14 males and 14 females, age between 23 to 56 (37 ± 9 years). They are from different origins (i.e. 8 from Asia, 5 from Africa and 15 from Europe) but all of them have stayed in Europe for at least one month before the commencement of the assessment. The sensitivity of their touch was screened with JVP Domes (Stoelting Company, 1997) prior to the assessment. The selected panel members were within the range of 0.6 to 1.8 mm discrimination performance.

The test was conducted by following the guidelines of AATCC evaluation procedure 5-2011 (American Association of Textile Chemists and Colorists, 2014), other than the author's newly developed method mentioned in Chapter 3 and already published (Binti Haji Musa, Malengier, Vasile, & Van Langenhove, 2019). After washing their hands, the panel members were acclimatized for 15 minutes before the test started. During this period, they were briefed about the execution procedure. The sample was placed on a non-metallic surface, with the surface to be evaluated uppermost. Warmth was assessed first, following the recommendation by AATCC 5-2011 procedure (American Association of Textile Chemists and Colorists, 2014). Next, the assessor touched the sample by lightly pressing it with the fingers and the palm of the hand to evaluate its smoothness and then he or she picked it up and pressed it between thumb and fingertips to assess its softness. The assessors were blindfolded throughout the test to prevent any incorrect judgment due to visual influence. A scale of 1 to 10 was used where a score 10 indicates the softest, smoothest or warmest fabric and a score of 1 is the extreme opposite. The scores given by the assessors were averaged for the analysis purpose. A thorough procedure to handle large sets of more than 10 samples by splitting them in several sessions was explained in the Chapter 3.

Each panel member received his/her own set of fabrics, to prevent any incorrect assessment due to repeated handling of the sample. Each sample had a size of 20x20 cm and was conditioned at least for 24 hours in standard atmospheric conditions.

5.4 Results and discussion

5.4.1 Analysis on objective testing with FTT

Each of the fabrics was tested with the FTT and only results of one side, labelled 'outside' or 'face' were considered as the analysis will be done on active touch which normally refers to the outside of a garment. Data cleaning was done before statistical analysis. The dataset was tested for outliers, and in case of an outlier in a sample, the mean value of the remaining sample is used instead in computing derived values like determination of the corresponding computed comfort index. The statistical analysis was done in an ipython notebook with Statsmodels module. The data is made available to public at github.ugent.be/UGentTextile/FTTAnalysis-Open.

FTT prediction on the comfort properties i.e. smoothness, softness and warmth is given in Table 5-2. These values are generated based on the 13 fabric indices measured by FTT. The means and standard deviation of the indices are tabulated in Table 5-3.

Table 5-2 Means and standard deviations (SD) of FTT comfort indices for the outsides of the 13 tested fabrics emphasising the out-of-range values for smoothness and warmth of fabric I.

		Fabric ID												
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**
smooth-ness active	**mean**	0.32	0.38	0.43	0.32	0.36	0.73	0.51	0.44	**1 (1.14)**	0.92	0.60	0.47	0.47
	SD	0.01	0.01	0.03	0.02	0.03	0.21	0.11	0.03	0.48	0.20	0.08	0.02	0.02
softness active	**mean**	0.56	0.56	0.58	0.47	0.54	0.58	0.36	0.44	0.69	0.57	0.56	0.38	0.40
	SD	0.01	0.01	0.02	0.01	0.01	0.07	0.05	0.02	0.20	0.09	0.03	0.02	0.02
warm-ness active	**mean**	0.65	0.65	0.60	0.65	0.60	0.25	0.43	0.54	**0 (-0.11)**	0.07	0.41	0.53	0.55
	SD	0.03	0.02	0.02	0.01	0.04	0.20	0.12	0.03	0.44	0.19	0.06	0.02	0.03

For comfort indices, fabric I – woven modal, was predicted as the smoothest, softest and coolest, fabric D – knitted cotton was roughest and warmest, and the stiffest is fabric G – woven lyocell micro , as can be visualized by the graphs in Figure 5-1. Based on the fabric indices in Table 5-3, fabric I – woven modal was measured with highest Qmax, and lowest CW, T, SFCa, SRAa and SRWe. The normalized values of the comfort indices should be within 0 to 1. Note that for I, smoothness value exceeded 1, and warmness was given in a negative value. These out-of-range values indicate possible errors as they were predicted outside the valid range which the FTT software reported as 1 or 0. This suggests that the tested fabric may be different than the fabrics used by SDL Atlas for the statistical models. A relatively high standard deviation was observed for the fabric for all the indices as shown by the error bars in Figure 5-1. Fabric D – knitted cotton has the highest BARe, CW, T, TCC, TCR, SFCa, SRAa and SRAe, also lowest value in CRR, CAR and RAR. BARa, BWa, BWe and RAR were found highest for fabric G – woven lyocell micro. The comfort values must be affected by these fabric indices. The fabrics with low thickness, F, G, I and J seems to have higher standard deviations. The correlation between the FTT comfort indices and fabric indices was investigated and discussed in Chapter 2.

There is a clear division for woven and knitted fabrics especially for smoothness and warmth. Woven is predicted as smoother and cooler than knitted, as can be seen in Figure 5-1. A one-way Analysis of Variance or ANOVA (significance level α=0.05) was carried out for variance analysis, together with a Tukey test. Woven and knitted types of fabric were treated separately in the analysis. The plots shown in Figure 5-2 indicate the results for Tukey test applied on the three comfort indices. The overlapping bars in the plots represent corresponding means of the samples while the un-overlapping designate significant difference in mean. For smoothness, sample A and D are clearly distinct from sample C, amongst knitted. All woven were almost the same, except for sample I which is the highest for the smoothness index. Sample D is far different from other knitted, and sample I is also different from other woven for softness prediction. For warmth, E and C can be distinguished from other knitted, while for woven, almost all samples can be classified in one group, except for F, I and J. Sample I is the farthest from the rest of woven samples.

Table 5-3 Means and standard deviations (SD) of FTT fabric indices for the outsides of the 13 tested fabrics, in wale (a) and course (e) direction

		Fabric ID												
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**
***BARa**	mean	85.78	102.13	100.06	155.45	112.52	90.54	173.23	126.27	116.26	135.80	58.96	132.36	140.72
	SD	2.28	13.24	5.15	19.39	10.57	20.46	17.16	7.19	16.34	12.65	3.83	10.16	12.41
***BARe**	mean	99.24	117.88	123.89	173.07	139.82	104.29	109.35	104.10	100.28	102.93	68.37	138.85	160.18
	SD	2.31	21.93	10.03	16.14	5.87	11.33	11.77	8.36	16.07	10.69	2.30	12.75	44.94
***BWa**	mean	264.71	346.68	294.12	575.11	336.81	566.97	1079.91	697.40	764.13	843.79	360.81	793.32	770.62
	SD	25.40	28.72	18.31	53.43	34.53	118.70	196.79	32.83	137.65	83.28	16.34	46.23	39.05
***BWe**	mean	316.31	402.78	375.80	574.83	405.02	442.63	581.21	499.13	453.50	557.74	370.66	538.88	492.65
	SD	17.90	45.71	34.33	26.14	25.81	23.86	75.24	24.82	128.51	24.60	40.79	53.12	34.26
CW	mean	404.23	399.22	292.25	423.12	282.92	81.31	157.52	202.60	58.06	78.40	155.15	194.77	214.55
	SD	94.17	68.47	15.25	22.84	68.22	45.11	86.03	23.63	18.51	11.57	8.35	22.07	32.35
CRR	mean	0.36	0.35	0.39	0.33	0.39	0.50	0.38	0.43	0.48	0.55	0.56	0.50	0.43
	SD	0.07	0.07	0.11	0.08	0.09	0.18	0.18	0.06	0.23	0.16	0.08	0.07	0.13
CAR	mean	618.61	646.76	895.40	588.81	880.80	3023.96	1920.95	1186.37	5288.86	4113.70	2004.28	1311.66	1203.45
	SD	164.84	117.38	164.46	31.06	242.34	1394.06	811.31	186.53	2702.20	1254.04	400.39	132.87	160.69
RAR	mean	2287.55	2077.16	3449.47	1941.44	5799.35	12719.64	24105.49	5798.47	11888.51	11395.26	2279.27	3616.27	4099.30
	SD	825.30	566.12	2073.99	162.52	5086.36	7236.57	15773.78	584.71	6766.22	4112.63	267.13	997.79	1139.47
T	mean	0.45	0.51	0.42	0.53	0.44	0.22	0.23	0.26	0.22	0.23	0.27	0.29	0.36
	SD	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
TCC	mean	39.85	46.82	40.04	49.24	41.34	26.51	28.03	31.34	27.80	28.23	29.03	30.64	37.73
	SD	1.48	2.17	0.84	0.68	2.12	1.17	1.35	0.93	0.72	1.13	1.02	0.64	0.98
TCR	mean	39.66	46.57	39.99	49.02	41.34	26.41	27.83	31.05	27.79	28.24	27.69	30.06	37.52
	SD	1.14	1.74	0.71	0.78	1.78	0.71	1.30	0.49	0.73	0.98	0.17	0.39	1.00
Qmax	mean	940.46	972.34	987.38	977.32	986.80	1218.65	1208.50	1190.27	1232.75	1211.15	1090.69	1067.39	1060.97
	SD	10.21	18.15	10.82	16.76	16.10	15.80	13.77	21.87	15.01	17.05	15.78	7.46	12.35
***SFCa**	mean	0.47	0.36	0.40	0.58	0.46	0.28	0.27	0.37	0.23	0.23	0.31	0.28	0.27
	SD	0.01	0.01	0.01	0.05	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.03
***SFCe**	mean	0.57	0.45	0.48	0.46	0.58	0.40	0.46	0.33	0.36	0.39	0.31	0.34	0.34
	SD	0.01	0.02	0.01	0.01	0.03	0.04	0.05	0.04	0.05	0.04	0.02	0.01	0.02
***SRAa**	mean	57.27	57.53	58.59	63.11	55.82	15.83	15.76	19.00	15.91	15.09	43.22	35.74	49.76
	SD	3.29	13.89	13.03	14.24	11.72	3.28	0.60	4.30	2.88	1.90	3.61	2.46	8.67
***SRAe**	mean	46.57	42.20	36.51	47.70	32.09	14.13	14.00	25.43	13.65	15.33	35.07	34.91	39.99
	SD	5.42	3.21	8.50	9.60	3.96	3.23	1.85	6.80	1.53	1.76	3.28	2.95	6.71
***SRWa**	mean	2.08	2.83	3.46	3.19	2.68	1.52	1.18	1.42	1.25	1.42	0.92	0.79	1.15
	SD	0.20	0.80	1.03	0.60	0.48	0.38	0.16	0.46	0.39	0.31	0.16	0.21	0.29
***SRWe**	mean	1.45	1.68	2.26	1.59	1.58	0.62	0.58	2.03	0.57	0.71	0.88	0.72	1.08
	SD	0.36	0.12	0.58	0.55	0.43	0.13	0.08	0.76	0.06	0.12	0.17	0.10	0.18

*Small letters following the indices indicates: a- wale direction; e- course direction.

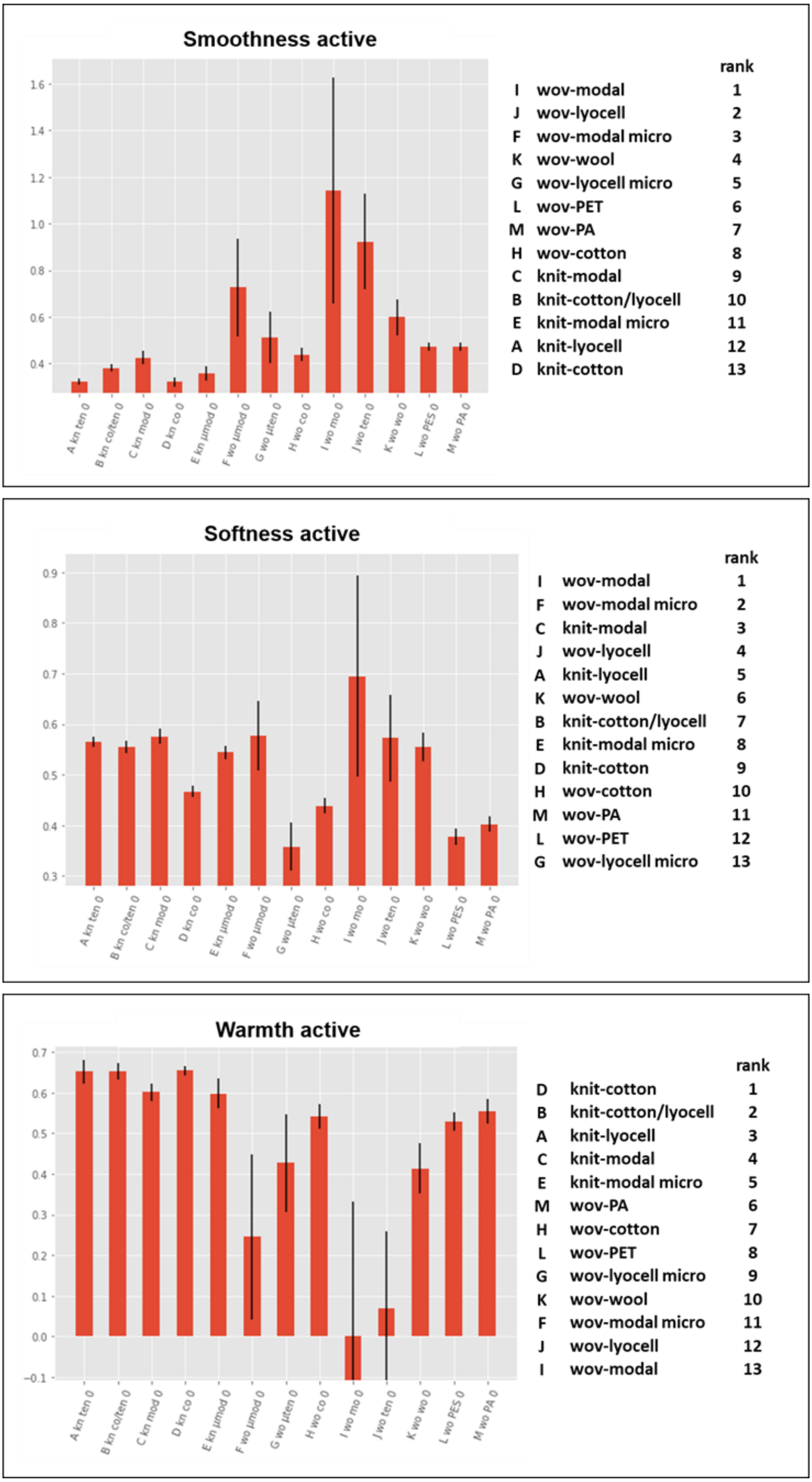


Figure 5-1 FTT comfort indices i.e, smoothness, softness and warmth prediction for the tested fabrics.

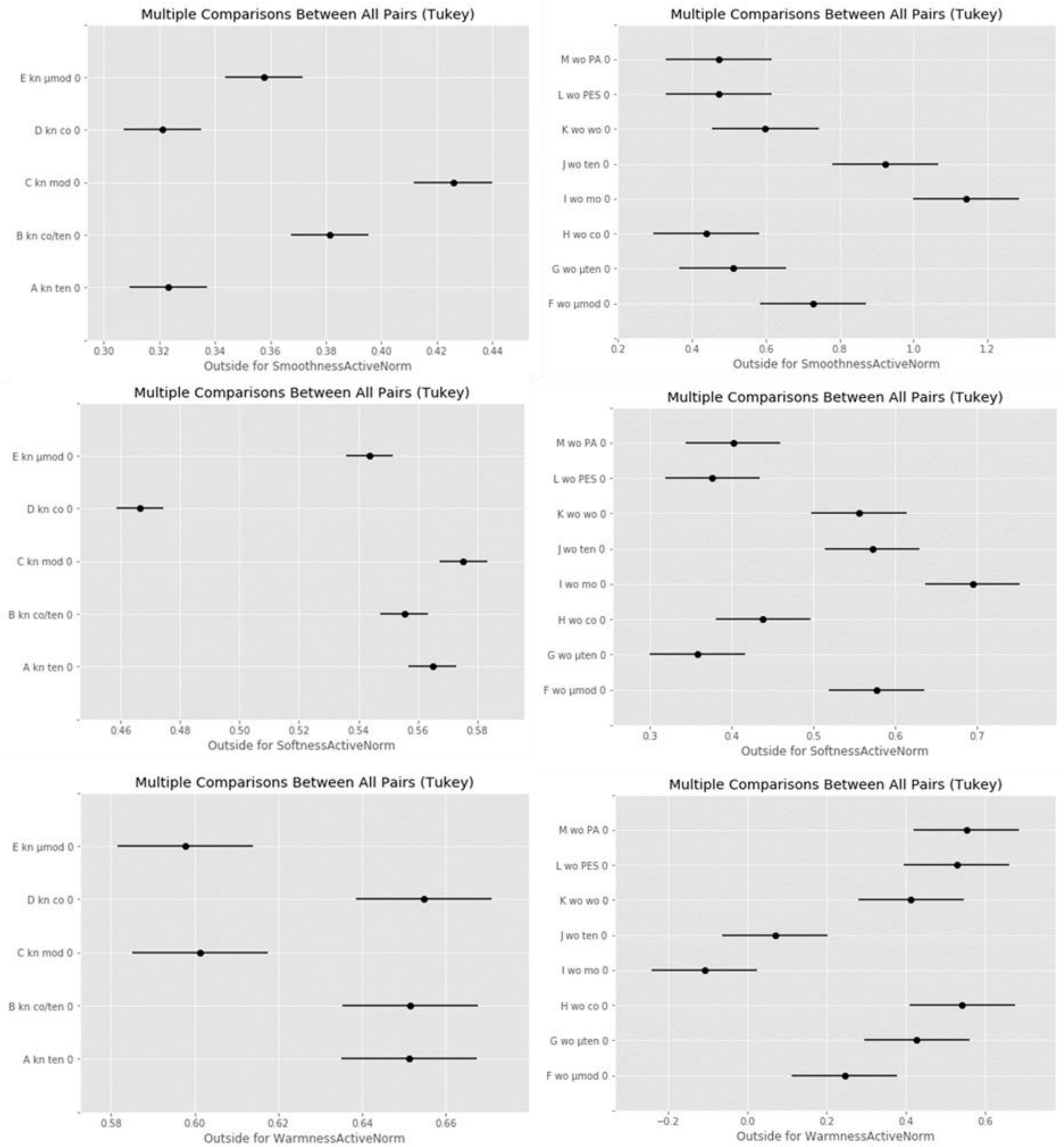


Figure 5-2 Graphics on ANOVA and Tukey HSD analysis showing un-overlapped bars if the samples are significantly different

Principle Component Analysis (PCA) was applied on the data as a dimension-reduction tool to reduce a large set of variables i.e. indices, to a small set that still contains most of the information. For that, the contribution or importance of each index needs to be checked. PCA uses orthogonal transformation to convert the original correlated data points into a set of linearly uncorrelated variables called principal components (PCs) (Jolliffe, 2002; Tang et al., 2017). The PCs has reduced number of parameters but still represent the actual data. Four PCs are needed to explain a total of 80% of the data which are ranked based on their eigenvalues, with a total of 20 original parameters from the measured and derived FTT indices (see Figure

5-3 and Table 5-4). PC 1 has poor correlation with all the original parameters. Similar results were obtained for other PCs, however they have one parameter which is moderately correlated for each of them. PC 2 increases with the increase of BWe. BARa would make PC 3 increase as it increases, and lastly the increment of SFCe will also increase PC 4. The connections of PC 1, 2 and 3 are given in a plot in Figure 5-4. From the results, it seems that the pattern in the data set is not pronounced and the variables are mostly poorly correlated with the PCs which suggest the unsuitability for this analysis for the FTT data.

The result from predictive models based on the objective evaluation should correspond to the perception of human. Therefore, to verify the finding, the relationship between objective-based and subjective evaluations will be discussed next.

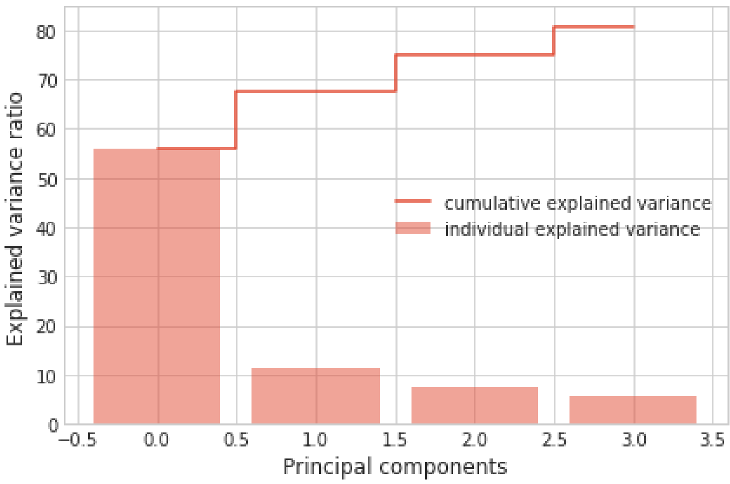


Figure 5-3 Graph showing the number of principal components and their percentage of variances explained

Table 5-4 The first four principal components for the FTT data highlighting the variables that correlate ≥ 0.500

variables	PC 1	PC 2	PC 3	PC 4
BARa	0.018	0.425	**0.565**	-0.098
BARe	-0.126	0.496	-0.266	-0.130
BWa	0.210	0.289	0.403	-0.118
BWe	0.092	**0.556**	-0.182	-0.140
T	-0.290	0.067	0.023	-0.045
CW	-0.275	0.021	0.138	0.092
CRR	0.140	-0.050	-0.253	-0.589
CAR	0.174	-0.027	-0.208	-0.112
RAR	0.225	0.134	0.011	0.362
TCC	-0.282	0.119	0.029	-0.060
TCR	-0.280	0.121	0.035	-0.056
Qmax	0.279	0.046	0.018	0.102
SFCa	-0.218	-0.110	0.256	0.140
SFCe	-0.174	0.158	-0.287	**0.500**

SRAa	-0.265	0.027	-0.006	-0.080
SRAe	-0.240	-0.130	0.064	-0.304
SRWa	-0.206	0.236	-0.329	0.105
SRWe	-0.212	-0.091	0.036	-0.075
RCD	-0.278	0.020	0.141	0.077
RRD	-0.256	-0.074	-0.054	-0.177

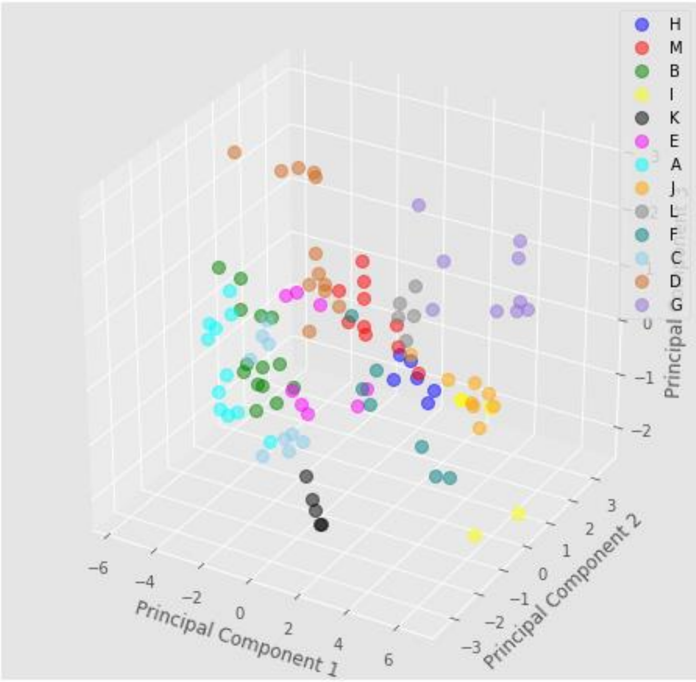


Figure 5-4 3D plot showing the relationships of PC 1, 2 and 3

5.4.2 Analysis on subjective tests

Subjective assessment was conducted with 28 assessors using a newly introduced blind-rate method presented in Chapter 3. A thorough analysis on the results is already included in the chapter, hence here, only selected results are discussed. Figure 5-5 shows the mean scores of the results for smoothness, softness and warmth judged by the human panels. For smoothness, fabric I – woven polyamide was chosen as the smoothest and fabric M – woven modal was the roughest. Woven cellulosic fabrics dominated the smoothest rank. However, the smoothest among knitted is fabric C – modal and fabric A – lyocell is the roughest. The human panel also selected fabric C – modal as the softest and warmest for knitted fabrics. From Figure 5-5, knitted and woven fabrics are discernibly distinguished as knitted were perceived as softer and warmer than woven. Amongst woven, fabric F – modal micro was chosen as the smoothest and fabric G – micro lyocell as the roughest and coolest as well. Fabric L – woven polyester on the other hand is the warmest amongst woven. Next, these results from the human panel will be compared with the prediction from FTT.

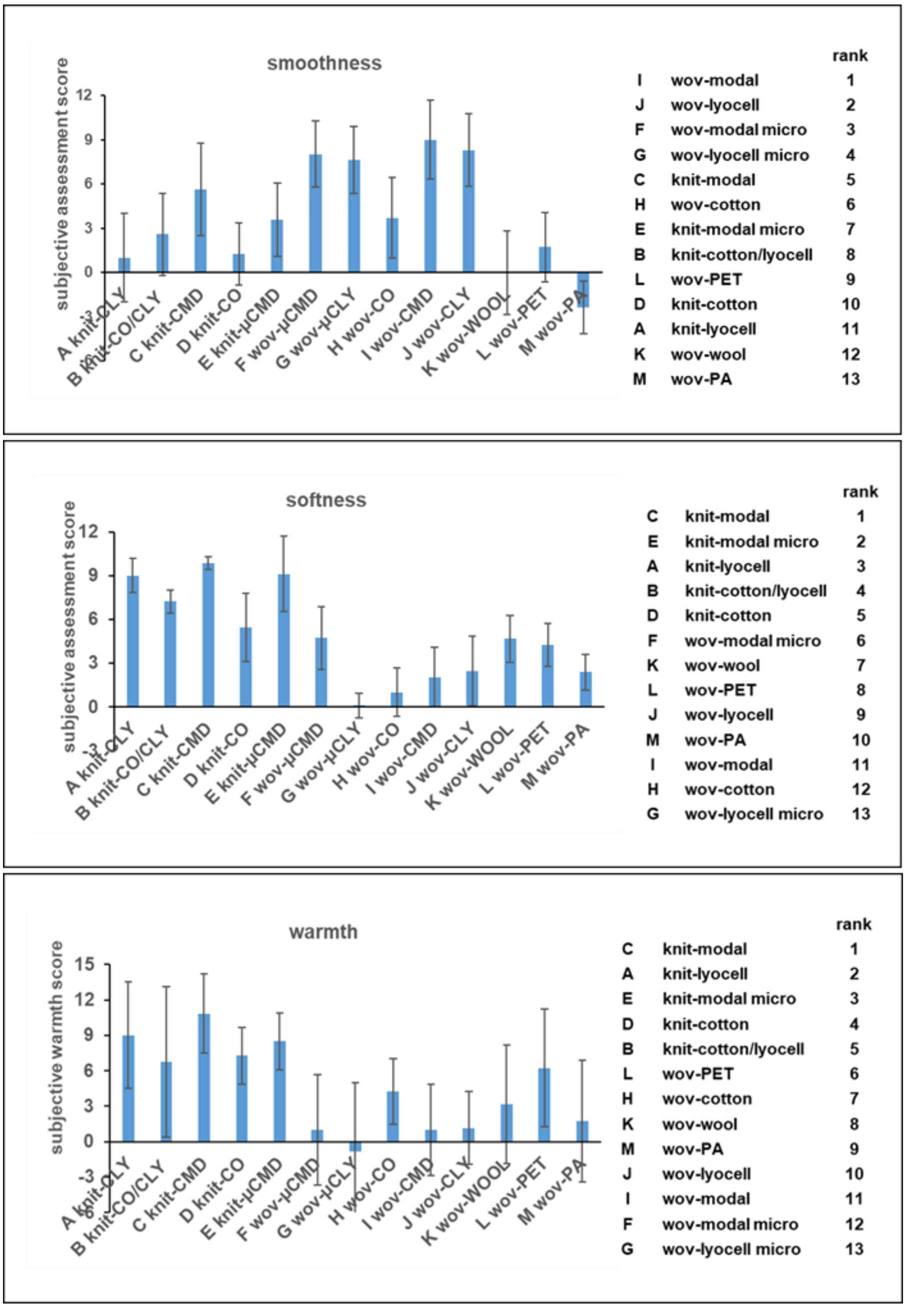


Figure 5-5 Results on human judgment for smoothness, softness and warmth

5.4.3 Relationship between objective and subjective measurement

5.4.3.1 FTT comfort models vs human assessment

The FTT predicted comfort values of the fabrics are compared with the human assessment. The device should have been able to quantify and compute the results as humans as that is its objective. For a brief overview of the comparison, Table 5-5 shows the rank for the highest and lowest values given by both approaches i.e. objective and subjective assessment which indicates that the FTT comfort values are partially not in correspondence with the human judgement. Good prediction is made for the smoothest fabrics for both woven and knitted and softness-stiffness attributes except for the woven softest fabric. For warmth, no match for the extreme values i.e. warmest and coolest.

To confirm the relationship of the two methods, a correlation and regression analysis was carried out, and the results are presented in Table 5-6. The Pearson's R value shows an average positive correlation between mean data from FTT and human assessments for smoothness and warmth i.e. R=0.66 and R=0.69 respectively. However, slightly lower values were obtained in case the full FTT data was in used. Figure 5-6 illustrates the relationship in full data. Although the FTT prediction was almost completely correct for the softness extremes in Table 5-5, surprisingly, no significant correlation was observed between these two assessments. The middle rank of the prediction must have a different arrangement that contributes to the insignificant correlation at 95% confidence interval i.e. $\alpha=0.05$. **The lack of correlation found means that the device could not interpret the touch properties of the fabrics as the panel did.** Further investigation is made to determine the indices picked up by the FTT comfort models. The results are discussed in the following sections.

Table 5-5 Rank of the highest and lowest values from FTT and human assessment

		FTT prediction		**human assessment**	
		highest (smoothest, softest, warmest)	lowest (roughest, stiffest, coolest)	highest (smoothest, softest, warmest)	lowest (roughest, stiffest, coolest)
smoothness	woven	I	H	I	M
	knitted	C	D	C	A
softness	woven	I	G	F	G
	knitted	C	D	C	D
warmth	woven	M	I	L	G
	knitted	D	E	C	B

Table 5-6 Pearson's R values for the relation between FTT comfort indices and human assessment

		FTT	
		means	all data
smoothness	human - means	0.66	0.56
softness		not significant	
warmth		0.69	0.59

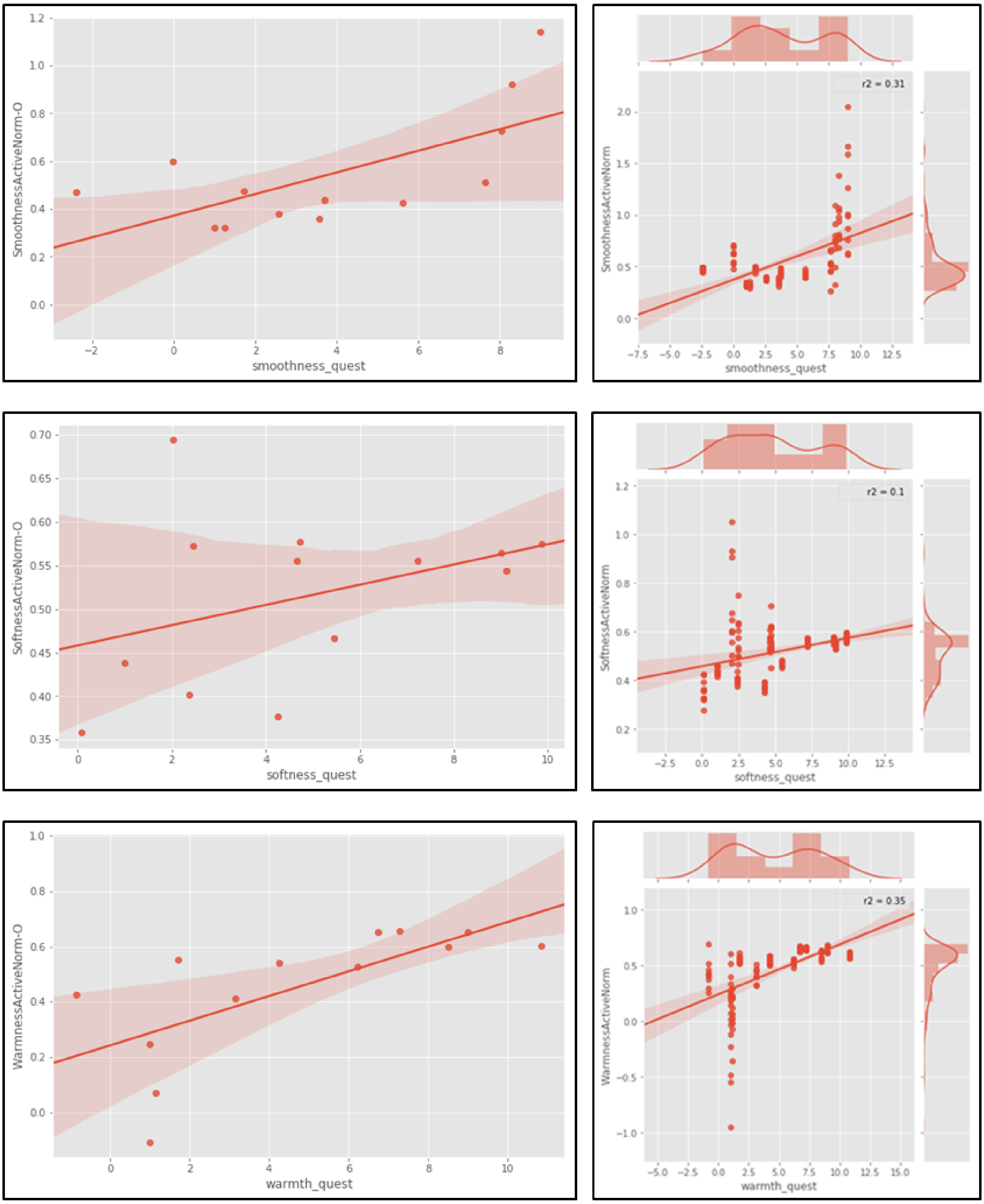


Figure 5-6 Relationship between FTT mean (left) and full data (right) with panel assessment results for smoothness, softness and warmth (x_quest refers to the result from panel assessment, xActiveNorm is that of FTT measurement)

5.4.3.2 Human assessment vs FTT fabric indices

Since the FTT comfort indices are computed based on the measured fabric indices, an investigation is done to analyse the relationship between the single fabric indices with the panel judgement. Apart from the indices given by the FTT software, several variables were derived and will be considered in the analysis. They are listed below;

- Average values for the indices measured in warp (a) and weft (e) directions i.e. bending and surface properties. A small letter ‘m’ is placed after the abbreviation of the indices which refers to the average, e.g. BWm – Bending Work average for warp and weft, SRAm – Surface Roughness Amplitude average for warp and weft.
- Approximate Insulation (INS) is T/TCC in m^2 K/W. This is approximated because the thickness T measured by FTT is not done according to ISO standard, and TCC is conductivity under compression.
- Relative Compression Distance or RCD is the distance traversed by the traction component of FTT to compress 1 mm of sample thickness at average force. It is computed as $(P_i - P_j)$/CAR where P_i and P_j are the 20% and 80% pressure level, respectively, so the middle 60% of the measurement considered.
- Relative Recovery Distance or RRD is the distance traverse by the traction component of FTT to recover 1 mm of sample thickness at average force. It is computed as $(P_i - P_j)$/RAR.

The correlation analysis was conducted and the results are tabulated in Table 5-7. Only the relationships with $p<0.05$ are listed in the table. Human perception of smoothness is most related to the FTT measurement of surface roughness and compression properties. SRA in warp, weft and average (a, e, m, respectively) showed strong negative correlations with human smoothness sensation i.e. higher surface roughness amplitude gives a rougher handle. Compression properties i.e. RAR, CAR, RRD, RCD and CW also showed a moderate to strong correlation, in which RAR and CAR are positively influenced while RRD, RDC and CW are correlated in negative manner. The higher the forces to compress the fabric and recover, the smoother the fabrics are. This is found to be in line with other works by various researchers that claimed compression as a big contributor to smoothness feel of fabrics (Hu et al., 2006; Vasile et al., 2019). Thermal indices i.e. Qmax and Approximate Insulation was moderately correlated with smoothness in positive and negative relationship, respectively. Smoothness can also be partially explained through the maximum energy needed for compression in which the higher the energy, the smoother the fabric. It is important to note that SFC had no direct significant correlation on smoothness.

Softness perception of human relates most with bending properties. Strong negative correlations for bending indices was obtained as in Table 5-7 which means softer fabrics make it more bendable. Other properties i.e. thermal, surface roughness, friction and compression also give a significant correlation to the softness sensation. Warmth was as expected highly correlated with thermal indices especially Qmax. Besides thermal, surface roughness and friction were also found to have good correlations with warmth. Many single indices were observed to have moderate to strong relationship with the assessed attributes by human panel. Therefore, statistical models will be generated to deduce the most influential indices which governed the touch perception with the aim of creating models with a lower error. The discussion about these models is in the next section.

Table 5-7 Pearson's R and p-values for correlation of human assessment with single FTT indices

	Pearson's R value	p-value
smoothness (human assessment vs FTT indices)		
smoothness and SRAe	-0.85	0.000
smoothness and SRAm	-0.77	0.002
smoothness and RAR	0.73	0.005
smoothness and RRD	-0.72	0.006
smoothness and CAR	0.70	0.008
smoothness and SRAa	-0.69	0.008
smoothness and Qmax	0.67	0.013
smoothness and INS	-0.61	0.025
smoothness and RCD	-0.57	0.040
smoothness and CW	-0.57	0.042
softness (human assessment vs FTT indices)		
softness and BWa	-0.89	0.000
softness and BWm	-0.87	0.000
softness and INS	0.84	0.000
softness and Qmax	-0.82	0.001
softness and SRAa	0.78	0.002
softness and SRWa	0.74	0.004
softness and SFCm	0.73	0.005
softness and SRAm	0.72	0.005
softness and T	0.72	0.005
softness and BWe	-0.71	0.006
softness and SRWm	0.71	0.006
softness and SFCe	0.70	0.007
softness and RRD	0.68	0.010
softness and RCD	0.68	0.010
softness and CW	0.65	0.016
softness and TCC	0.64	0.019
softness and TCR	0.63	0.020
softness and SFCa	0.62	0.024
softness and SRAe	0.61	0.027
softness and RAR	-0.60	0.031
softness and SRWe	0.56	0.045
warmth (human assessment vs FTT indices)		
warmth and Qmax	-0.87	0.000
warmth and INS	0.86	0.000
warmth and RCD	0.82	0.001
warmth and SRAa	0.81	0.001
warmth and SRWm	0.81	0.001
warmth and SRAm	0.80	0.001
warmth and T	0.79	0.001
warmth and CW	0.79	0.001
warmth and SRWe	0.78	0.002
warmth and BWa	-0.77	0.002
warmth and SFCa	0.76	0.003

warmth and SFCm	0.75	0.003
warmth and SRWa	0.75	0.003
warmth and SRAe	0.74	0.004
warmth and RRD	0.74	0.004
warmth and TCC	0.73	0.005
warmth and TCR	0.73	0.005
warmth and RAR	-0.72	0.005
warmth and BWm	-0.72	0.005
warmth and CAR	-0.69	0.010
warmth and SFCe	0.59	0.033

5.4.4 Determination of new predictive comfort models

As the predictive models used in FTT were partially not corresponding to the touch perception of human, new predictive models are developed. It is important to investigate on the indices picked up by the models so that a further understanding can be developed on the properties underlining the main tactile attributes. A comparative analysis between the new models and the ones that were previously reconstructed from thousands of FTT data (information in Chapter 2) will give a clear overview on the fundamental differences between the fabrics, and the indices that constructed the models.

The new models are generated by utilizing the python Statsmodels package. Only linear models were developed which only consider linear terms. For that, the ordinary least squares (OLS) combined with a stepwise regression was employed based on adjusted R^2. Terms i.e., FTT indices, were added as long as the adjusted R^2 of the model increases. At the same time, the relevance of the obtained coefficients was observed as terms were added. For that, the p-value for the t-statistics needed to be below 0.05 for the terms to be retained. This allows to construct an optimal model.

The models based on the means of the FTT indices, as well as models using the full FTT data are considered, and shown in Table 5-8 and Table 5-9, respectively. It can be seen that there are several possible models for fabric smoothness, softness and warmth properties obtained from the combination of the original FTT fabric indices and also the derived indices. The models are given a short identification code as in the table for easy reference and they are arranged in a sequence starting from the highest obtained adjusted R^2. All p-values are less than 0.05, hence the listed models are significant. The closer the adjusted R^2 value to 1, the more indices are included in the models which proves that the tactile feel of smoothness, softness, and warmth are contributed by a collective mechanical and thermal properties of the fabric. Nevertheless, only the most influenced indices are retained in the model. In case of missing values given by the FTT during a measurement, a NaN sign (not a number) will appear, and they will not affect the calculation in the analysis, except that they reduce the valid number of repeats for the sample sets. Nevertheless, a column is added in our database to include the index in which the missing values are changed to mean values. This new column is given an extension of '_comp' following the index related to it, e.g. T_comp and RAR_comp, and they can also be selected in the full data model as shown in Table 5-9. Other extensions to the index i.e. 'a', 'e' and 'm' refer to the warp direction, weft direction, and average of warp and weft, respectively, as consistently used in other parts of this thesis.

Smoothness models i.e. SM 1, SM 2 for mean data and SMF 1 and SMF 2 for full data, have large contribution by surface roughness (SRA, SRW) and compression properties (CAR) of the fabrics. A lower roughness amplitude and bigger roughness wavelength indicates a smoother fabric. A higher compression or recovery rigidity CAR/RAR would also explain a smoother handle of the fabric. Models SM 2 and SMF 2 exclude the effect of compression and the data can still fit for >70% of smoothness attribute which means that SRA and SRW alone hold a big contribution to the property.

Softness models are dominated by bending properties (BW, BAR). A lower bending work indicates that the fabric is more bendable, hence increases the softness. On the other hand, an increase in bending rigidity BAR for the same bending work BW would make the fabric feel softer. Typically, BW and BAR are correlated however as shown in Table 2-4 with the same sign. Hence, the BAR term here only serves to distinguish under equal BW value. The result of more BAR and hence generally more BW according to Table 2-4, will normally also be less soft fabric, except in the case BW did not change accordingly. Models SO 3 and SO 4 show only the contribution of bending properties towards the softness, in which >75% of data fit to the prediction line which allows to conclude that bending is highly contributing to softness attribute.

Warmth is inclined towards the thermal property i.e. Qmax, in which a decrease in Qmax or thermal maximum flux is a sign of a warmer fabric feel. Other thermal indices, TCC and TCR are also seen in WA 1, WA 2, WAF 1 and WAF 2 models. These indices are negatively related to the warmness feel of the fabric i.e. a higher TCR and TCC, the colder the fabric is, and vice-versa. An almost perfect fit data at adjusted R^2= 1.0 (RMSE=0.013) is obtained for WA 1 model. However, this model features 11 indices from all the modules measured by FTT i.e thermal, bending, compression and surface.

Table 5-8 New statistical models for fabric smoothness, softness and warmth based on mean data of FTT measurement

	Statistical models based on mean FTT data				
	Models		**Adj. R^2**	**p-values**	**RMSE**
Smoothness	SM 1	11.591 – 0.279 SRAe + 2.436 SRWa + 0.001 CAR + 0.023 CW – 0.303 TCC	0.958	<0.030	0.56
	SM 2	8.173 - 0.269 SRAm + 3.282 SRWm	0.778	<0.010	2.02
Softness	SO 1	34.305 – 0.009 BWa + 0.050 BARm – $6.2.10^{-5}$ RAR – 0.010 Qmax – 0.116 SRAe – 1.285 TCC + 85.372 T + 1.385 SRWa – 5.364 SFCm	0.999	<0.020	0.04
	SO 2	69.117 – 0.007 BWa – 0.047 Qmax – 0.254 SRAm	0.922	<0.010	0.79
	SO 3	10.238 – 0.021 BWm + 0.049 BARm	0.843	<0.020	1.68
	SO 4	11.431 – 0.011 BWa	0.783	<0.001	1.81

Warmth	WA 1	101.429 – 0.071 Qmax + 4.672 SRWm + 3.638 TCC – 0.163 SRAa – $3.060.10^{-4}$ RAR + 0.055 BARe + 0.001 CAR – 4.108 TCR – 17.914 CRR + 6.457 SFCe – 0.184 SRAm	1.000	<0.050	0.01
	WA 2	48.846 – 0.034 Qmax + 3.800 SRWm – 0.359 TCC	0.891	<0.020	1.44
	WA 3	24.339 – 0.021 Qmax + 2.501 SRWe	0.815	<0.040	1.65

Table 5-9 New statistical models for fabric smoothness, softness and warmth based on full data of FTT measurement

	Statistical models based on full FTT data				
	Models		**Adj. R^2**	**p-values**	**RMSE**
Smoothness	SMF 1	2.620 – 0.152 SRAe + 2.360 SRWm + 0.001 CAR_comp – 0.076 SRAa + 9.691 SFCe_comp	0.840	<0.005	1.29
	SMF 2	3.599 – 0.193 SRAm + 2.492 SRWm + $6.970.10^{-4}$ CAR_comp + $6.500.10^{-5}$ RAR_comp + 6.162 SFCm – 2.226 CRR_comp	0.815	<0.050	2.02
	SMF 3	8.660 - 0.201 SRAe_comp + 2.698 SRWm – 0.072 SRAa	0.773	<0.001	2.07
Softness	SOF 1	25.440 – 0.007 BWa + 8.984 SFCe – 0.015 Qmax – 4.089 SFCa + 0.900 SRWa_comp – 0.092 TCR – 0.042 SRAe	0.952	<0.005	0.61
	SOF 2	28.935 – 0.006 BWa – 0.016 Qmax – 0.407 TCR + 1.158 SRWm – 0.076 SRAm + 2.618 CRR + 3.656 SFCm – 53.072 RRD + 30.069 T_comp	0.925	<0.050	0.70
	SOF 3	29.142 – 0.005 BWa_comp – 0.016 Qmax_comp – 0.075 SRAm + 1.253 SRWm – 0.007 CW _comp + 4.639 SFCm + $1.860.10^{-4}$ CAR_comp – 0.622 TCR_comp + 49.731 T_comp + 0.010 BARe_comp	0.910	<0.020	0.95
	SOF 4	35.148 - 0.008 BWm – 0.024 Qmax_comp + 6.609 SFCm – 0.006 CW_comp – 0.063 SRAm + 0.755 SRWm + $1.850.10^{-4}$ CAR_comp	0.889	<0.030	0.82
Warmth	WAF 1	47.343 – 0.033 Qmax – 0.004 BWa + 2.091 SRWm – 0.159 TCR – 0.103 SRAm – $4.900.10^{-5}$ RAR_comp + 0.020 BARm	0.893	<0.050	1.04
	WAF 2	50.825 – 0.036 Qmax_comp + 2.382 SRWm – 0.210 TCC_comp – 0.097 SRAm – $6.000.10^{-5}$ RAR_comp + 28.238 RCD_comp	0.865	<0.030	1.07
	WAF 3	21.361 – 0.017 Qmax_comp + 1.483 SRWe _comp – 0.003 BWa + 3.961 SFCe	0.859	<0.040	1.69

The models are valid within the range as defined in the fingerprints in Figure 5-7, Figure 5-8, Figure 5-9 and Figure 5-10. The range is based on the FTT fabric indices values which are normalized in a scale 1-10 for the plots, based on the minimum and maximum values given specifically for each index as shown in Table 5-10 and previously given in Table 2-5 in Chapter 2. The bigger the area of shaded plots, the wider the range covered by the indices. The overlapping finger prints show the convergence of the indices by both type of fabrics. From the figures, it can be seen that woven fabrics covered a bigger area for the measured indices especially BWa, CAR and RAR. These fingerprints become the basis for fabric selection in the modelling in order to determine the boundary in which the models are valid.

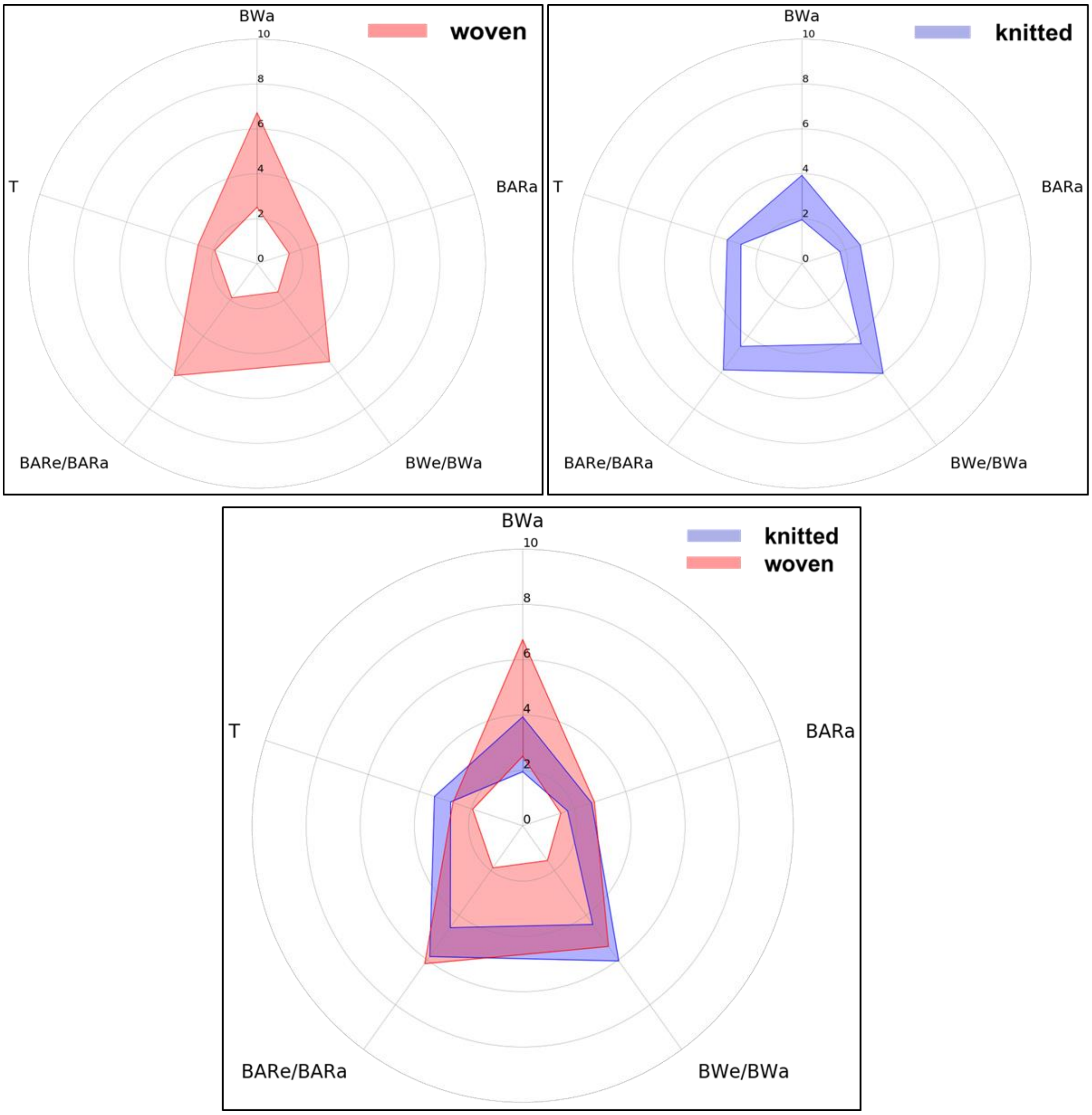


Figure 5-7 Bending fingerprints of tested woven and knitted fabrics, and also their overlapped plots for BWa, BARa, BWe/BWa, BARe/BARa and T

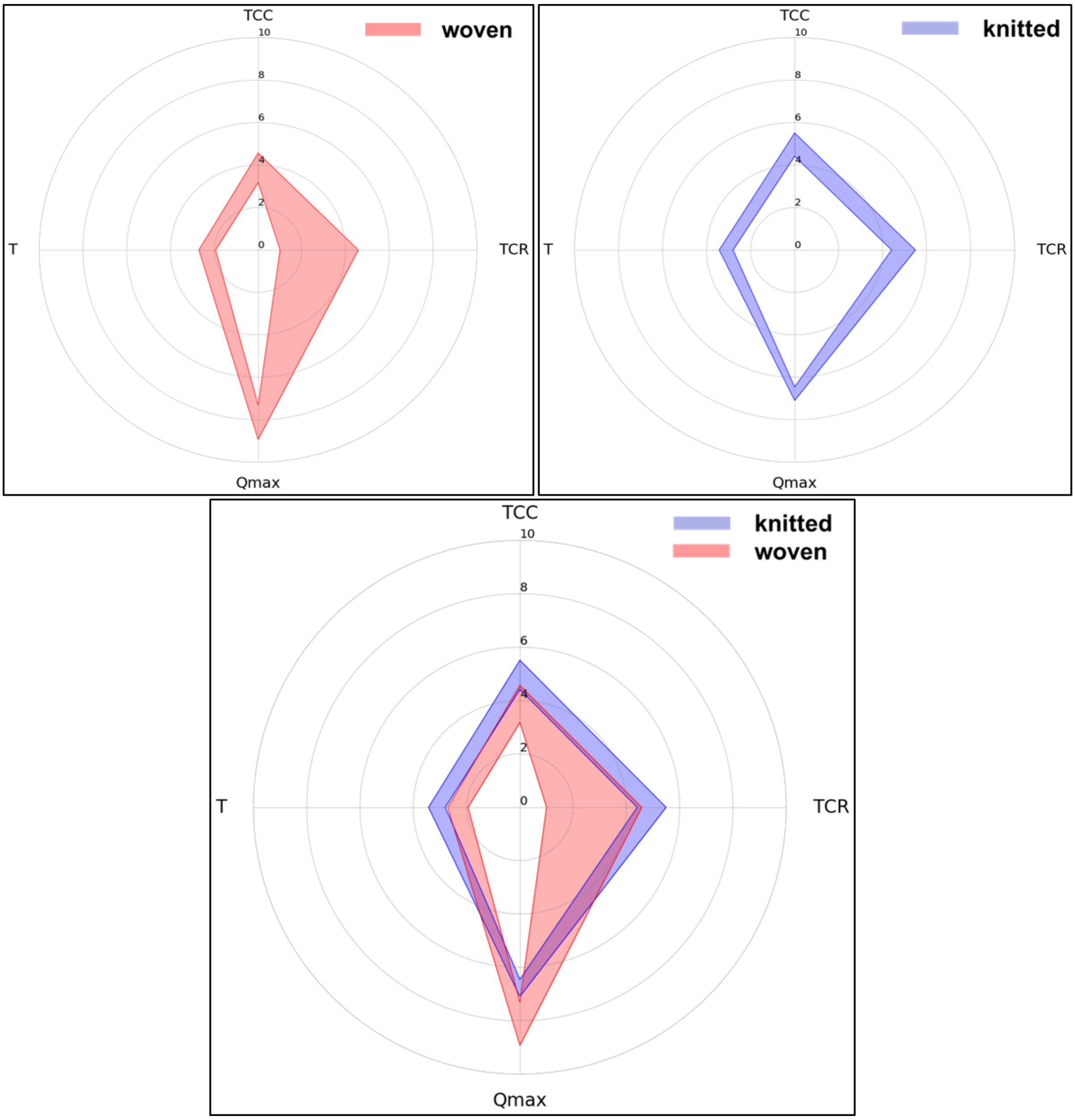


Figure 5-8 Thermal fingerprints of tested woven and knitted fabrics, and also their overlapped plots for TCC, TCR, Qmax and T

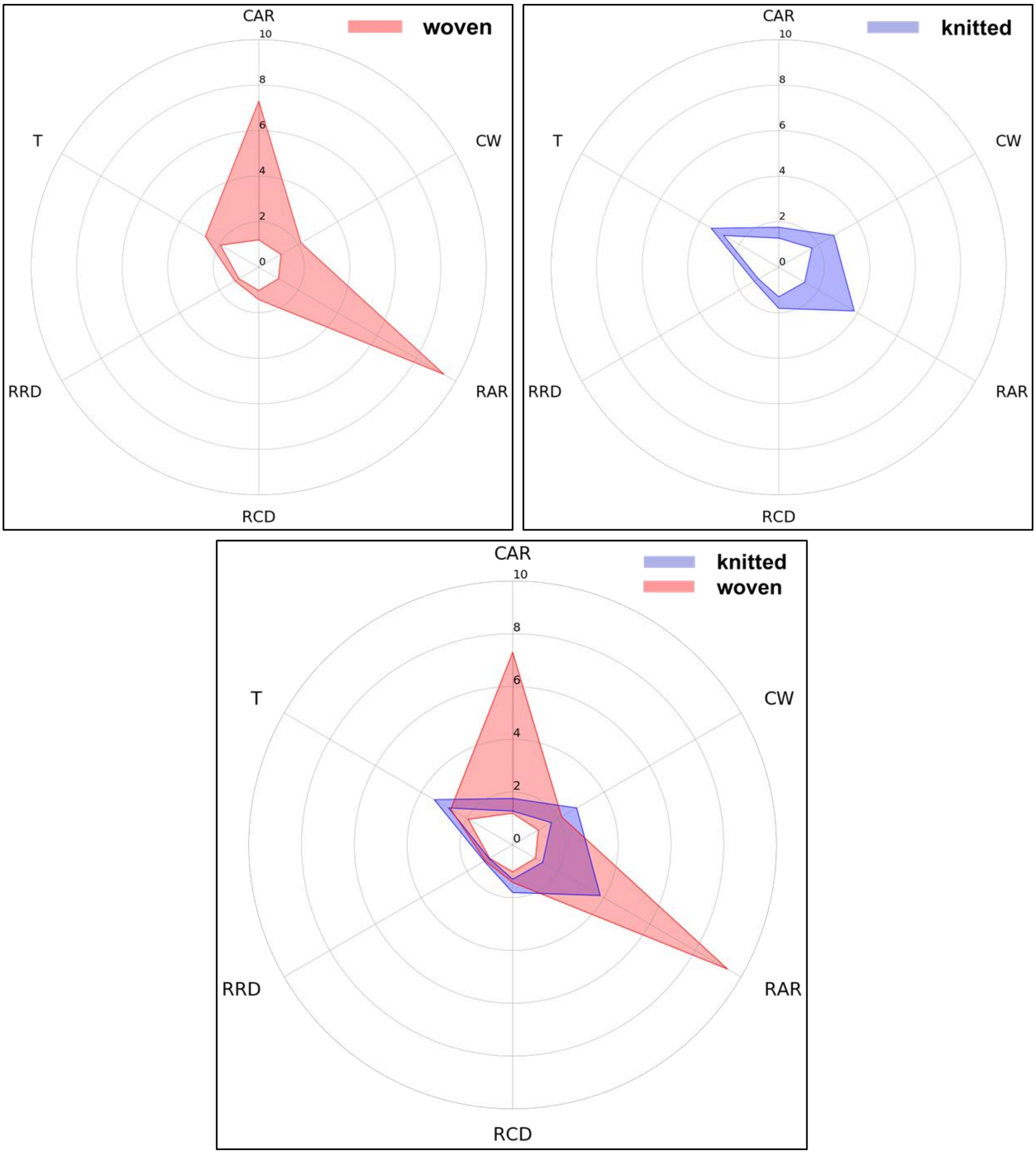


Figure 5-9 Compression fingerprints of tested woven and knitted fabrics, and also their overlapped plots for CAR, CW, RAR, RCD, RRD and T

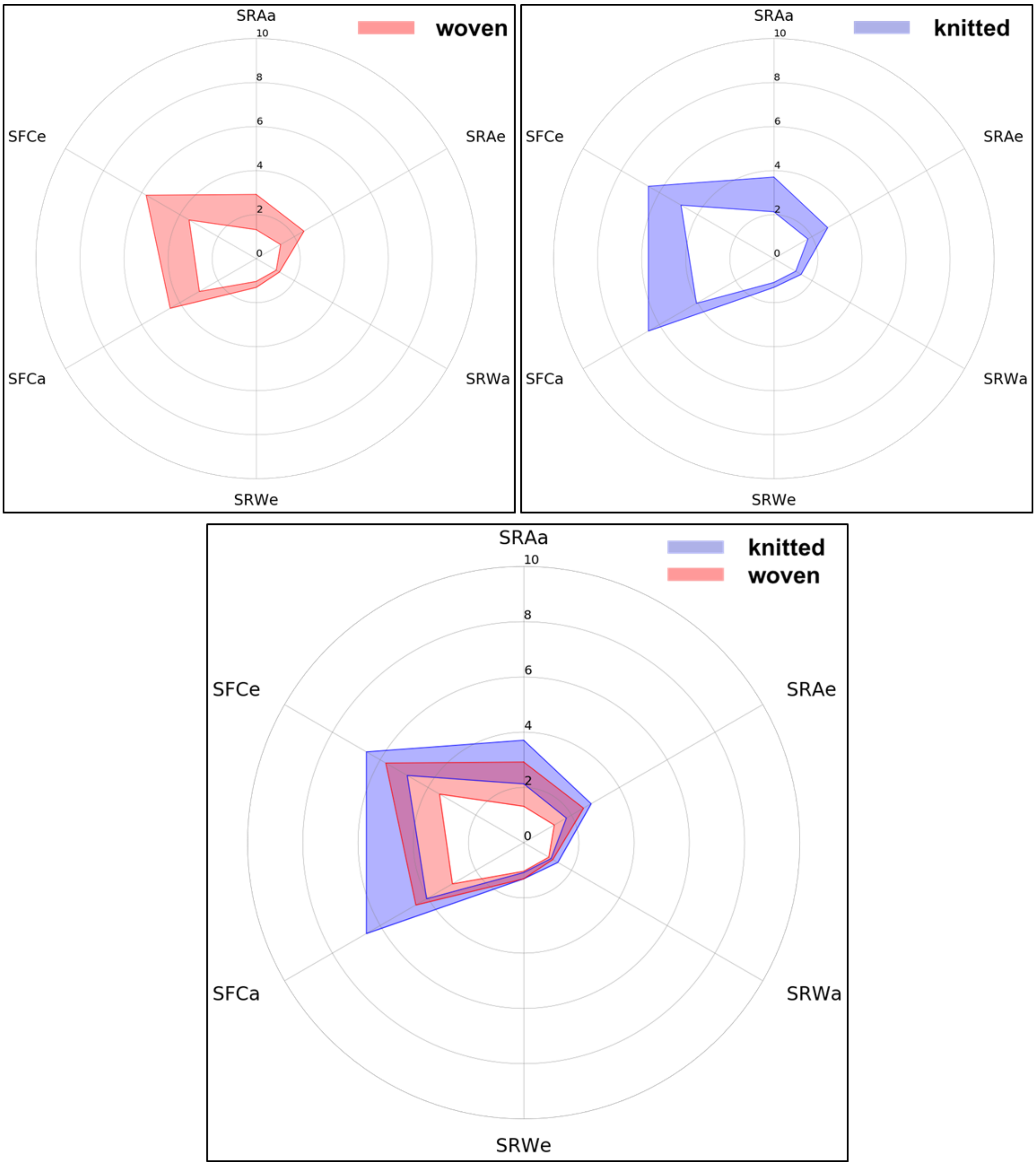


Figure 5-10 Surface roughness and friction fingerprints of tested woven and knitted fabrics, and also their overlapped plots for SRAa, SRAe, SRWa, SRWe, SFCa and SFCe

Table 5-10 Normalized values for the tested fabrics based on the maximum and minimum values of FTT fabric indices

	Min & max rescaling applied to normalize	woven		knitted	
		min	max	min	max
BARa	0 →1 1000→10	1.48	2.79	1.75	2.68
BARe	0→1 1000→10	1.00	3.05	1.75	2.78

BWa	0→1 2000→10	2.52	6.73	1.96	3.94
BWe	0→1 2000→10	1.87	4.15	2.27	3.69
T	0→1 2→10	1.95	2.71	2.80	3.43
CW	0→1 2500→10	1.13	2.14	1.69	2.80
CRR	0→1 1→10	2.44	7.75	2.80	5.32
CAR	0→1 15000→10	1.21	7.29	1.28	1.76
RAR	0→1 45000→10	1.00	9.40	1.32	3.83
TCC	0→1 100→10	3.17	4.57	4.42	5.51
TCR	0→1 100→10	1.00	4.58	4.40	5.49
Qmax	200→1 1400→10	7.30	8.92	6.45	7.09
SFCa	0→1 1→10	2.98	4.51	4.06	6.58
SFCe	0→1 1→10	3.52	5.77	4.87	6.58
SRAa	0→1 300→10	1.32	2.92	2.13	3.71
SRAe	0→1 300→10	1.28	2.50	1.78	2.82
SRWa	0→1 100→10	1.05	1.22	1.14	1.43
SRWe	0→1 100→10	1.03	1.31	1.08	1.30
RCD	0→1 1→10	1.02	1.42	1.30	1.80
RRD	0→1 1→10	1.01	1.20	1.03	1.24

The models tabulated here are compared with the reconstructed models of FTT given in Chapter 2, section 2.4.1. The simplified version of the models is repeated here in Table 5-11 below. Roughness index in FTT smoothness model only appears as the sixth term, unlike the new generated model where roughness indices are the main terms included in the models. Instead, compression index CAR is selected as the first term, followed by BWa. For softness, both models from FTT and the new generated version includes bending index BW as the main terms. Warmth reduced model of FTT does not pick up any thermal indices. However, in the full model, TCC is shown as the fourth term in the model. Since the first two terms i.e. CAR and T are already highly contributed to the fit of the model (high adjusted R^2=0.983), hence the addition on TCC index seems to have a minor increment to the warmth model.

Table 5-11 FTT reconstructed reduced models

	FTT reconstructed model (reduced model)
Smoothness	0.426 + 1.530e-04 CAR – 6.000e-05 BWa + 2.622e-03 TCR+ 2.360e-04 CW – 6.694e-01 T + 1.325e-02 SRWa
Softness	6.064e-01 – 2.460e-04 BWe + 1.810e-04 CW + 6.800e-05 CAR – 2.130e-04 BWa
Warmth	6.609e-01 – 1.630e-04 CAR + 1.668e-01 T

To be able to see how a single property changes the characteristics and influences the touch sensation as in the model, some possible actions could be applied on the fabrics. Such actions are like ironing and washing. Ironing process requires a more delicate handling. Since the ironed fabrics can be easily crumpled or deformed back to un-iron state by movements, special handling process need to be exercised. In addition, the time gap between ironing and testing might also create some changes to the samples. Instead of measuring the pure effect of ironing, some conditional factors would be included in the measurement and affect the results. On the other hand, washing process is simpler to implement and the methods are very common. Additionally, variations i.e. number of washing cycles and washing methods can also be exercised thus providing more options in the experiments. After considering the possibilities for both methods, washing method is selected, not ironing. Through the action, we expect some indices of FTT will change due to the changes in the handle of the fabrics. The validation of the new created models will be done with the washed samples in order to see the consistency of the chosen indices within a model.

5.5 Effect of washing on FTT indices

5.5.1 Methodology

Three types of washing variables were introduced to the fabrics i.e. zero, one and five washing cycles or simply 0×, 1× and 5×. The 0× means the non-washed treatment which were the same samples like in the previous analysis. For 1× and 5× washes, the washing process was done using a Wascator FOM71 CLS, a type A, front-loading washing machine from James H. Heal & Co Ltd. The process followed washing procedure 4N which was pre-programmed in the machine. However, for wool fabrics, 4H procedure was imposed as it is much gentler and suitable for this fabric. Reference detergent 3 that consists of ECE non-phosphate, sodium perborate tetra hydrate and tetra acetyl ethylene diamine (TAED) were added into the washing machine and polyester ballasts were also added to the fabrics under test in order to achieve the specified weight in the reference washing machine. Before washing, the fabrics were given an overlocked stich around the perimeter to secure the edges from fraying. After washing, the fabrics were line-dried in still air under ambient condition. All the steps were in accordance with ISO 6330:2012(E) standard on 'Textiles – Domestic washing and drying procedures for textile testing' (International Organization for Standardization (ISO), 2012). The changes in fabric handle were then quantified by the FTT. After being given some mechanical forces through washing, the fabrics were expected to be physically deformed, thus resulting in changes to the FTT indices when measured. Nevertheless, it should still be sufficiently within the same range from the previously measured 0× wash fabrics. To validate the models generated earlier, five fabrics were selected from 5x washes and 2 from 0x wash for subjective assessment by six assessors and the results are discussed in the following section. The selected fabrics are shown in Table 5-12.

Table 5-12 List of fabrics for validation experiment

	Selected fabrics (5× washes)	**Reference fabrics (0× wash)**
smoothness	B knit-CO/CLY C knit-CMD D knit-CO I wov-CMD M wov-PA	I wov-CMD M wov-PA
softness	C knit-CMD D knit-CO E knit-μCMD G wov-μCLY L wov-PET	C knit-CMD G wov-μCLY
warmth	C knit-CMD B - knit-CO/CLY E knit-μCMD G wov-μCLY L wov-PET	C knit-CMD G wov-μCLY

5.5.2 Results and discussion

5.5.2.1 Variation of FTT fabric indices with number of washing cycles

Washing is known to affect the handle of fabric to a certain extent. However, no single index was observed to be highly influenced or changed by the process. The highest correlation obtained is with BARm (R=0.39) which suggest only a poor connection of the relationship, see plot in Figure 5-11 showing that higher BARm is typically associated with less washing. That is, due to washing, the fabric bends more easily. Nevertheless, the number of washes was found to strongly affect several indices collectively in which six indices i.e. BARm, TCR, SFCm, Qmax, BWm, and SRWm yield R=0.76 for the interaction. That model is given as 17.859 - 0.070BARm + 0.075TCR -12.030SFCm - 0.013Qmax + 0.011BWm + 1.015SRWm, with $p<0.001$. From the model, we learn that an increase in the number of washing cycles correlates with decreasing BARm, increase of TCR, and decreasing SFCm as the three main terms. Further correction on the model is given by increase of washings correlating with decrease in QMax, and similarly increase in BW and SRWm (see Figure 5-11). Figure 5-12 shows the region covered by the fingerprints of 0× and 5× washes, which indicates that the changes of most indices are still sufficiently within the range used in the new predictive models.

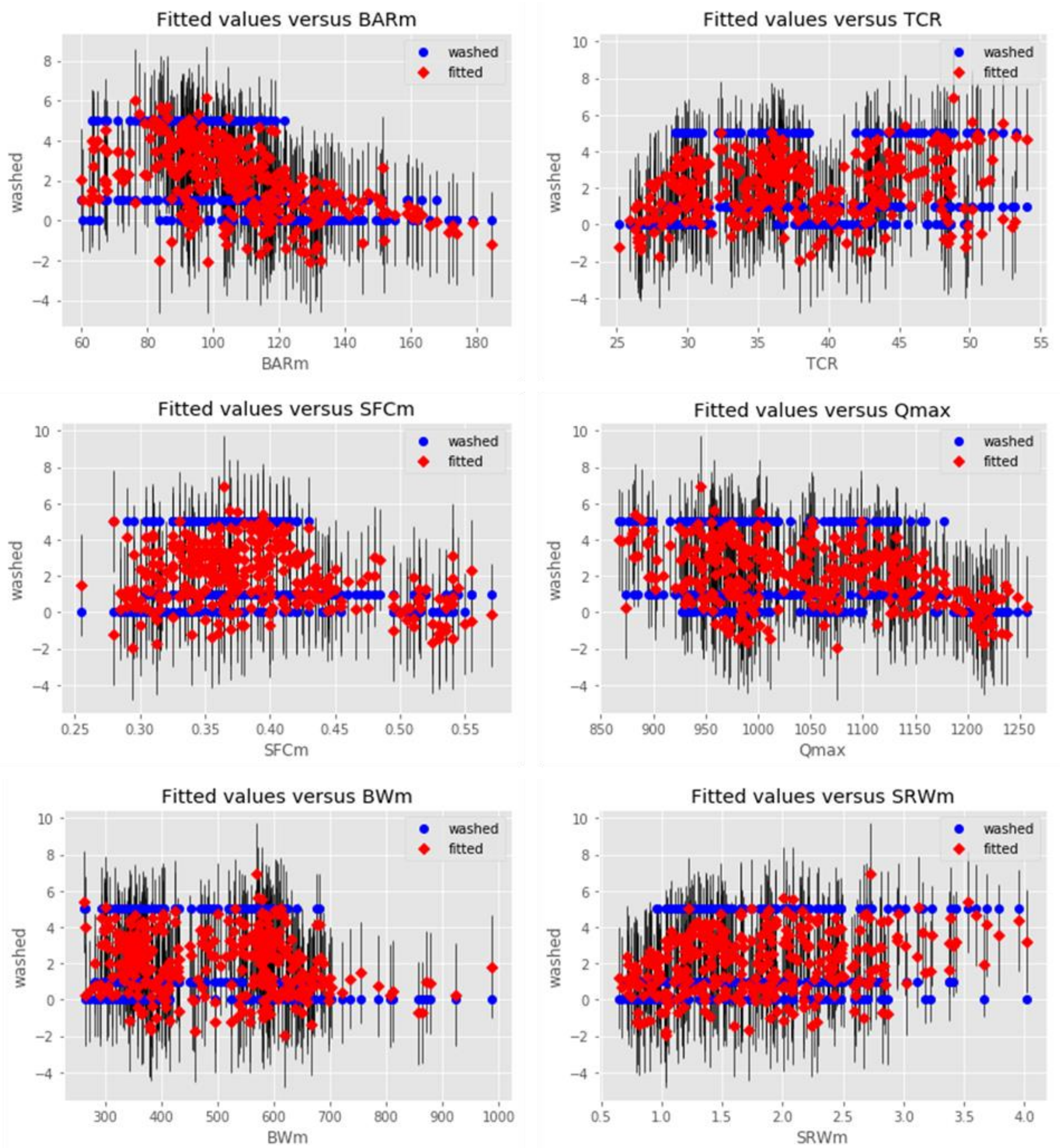


Figure 5-11 Relationship between number of washes versus BARm, TCR, SFCm, Qmax, BWm and SRWm

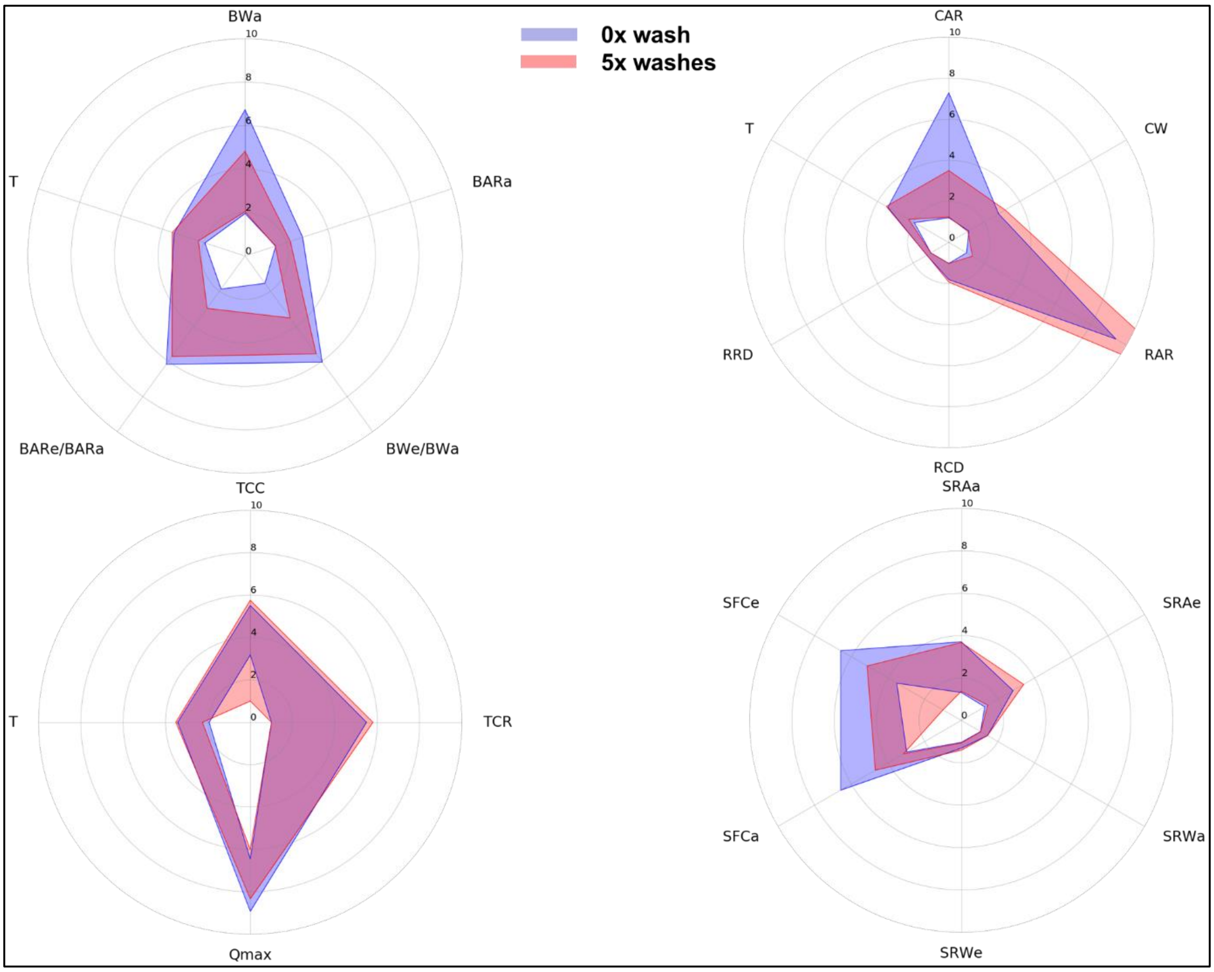


Figure 5-12 Bending, compression, thermal and surface fingerprints showing the regions covered by 0× and 5× washes fabrics

5.5.2.2 Validation of the models with human assessment

To validate the models created earlier, five types of fabrics that have been washed for five times were randomly selected. Two samples of 0× wash were also chosen from the highest and lowest values of touch perception given by the panel members during the previous assessment. These two samples were regarded as reference. Six panel members were asked to evaluate the samples for three attributes i.e. smoothness, softness and warmth. For each attribute, seven samples were assessed; five samples of 5× washes plus two reference samples taken from 0× wash. The evaluation follows the blind-rate procedures which was mentioned in Chapter 3, except this time, only one session was needed, allowing to normalize the output with the previous testing. Correlation analysis was done and the results are given in Table 5-13 and Table 5-14, for the mean and full data models, respectively. The model error, shown by the root-mean-square error (RMSE), or also known as root-mean-square deviation (RMSD) is computed for each model. RMSE is a measure of the deviations of the predicted values and the actual data from human assessment. The values were first normalized using a common feature scaling technique. Then, the computation for RMSE is done based on the equation below, where n is the number of tested samples i.e. 7 samples. RMSE is always a positive number, and a value of 0 indicates a perfect fit of the prediction to the actual data, which is almost never achieved in practice. Hence, a lower RMSE is targeted. The best models are selected based on this value, and also the Pearson's R from the correlation analysis.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} \|prediction_i - actual_i\|^2}{n}}$$

Table 5-13 Correlation analysis results for human smoothness, softness and warmth vs FTT mean data models predictions

		Model	Pearson's R	p-value	RMSE
smoothness	SM 1	11.591 – 0.279 SRAe + 2.436 SRWa + 0.001 CAR + 0.023 CW – 0.303 TCC	0.89	0.007	2.41
	SM 2	8.173 - 0.269 SRAm + 3.282 SRWm	0.93	0.002	2.35
softness	SO 1	34.305 – 0.009 BWa + 0.050 BARm – $6.2.10^{-5}$ RAR – 0.010 Qmax – 0.116 SRAe – 1.285 TCC + 85.372 T + 1.385 SRWa – 5.364 SFCm	0.91	0.005	2.23
	SO 2	69.117 – 0.007 BWa – 0.047 Qmax – 0.254 SRAm	0.71	0.074*	3.48
	SO 3	10.238 – 0.021 BWm + 0.049 BARm	0.83	0.022	2.82
	SO 4	11.431 – 0.011 BWa	0.87	0.011	2.36
warmth	WA 1	101.429 – 0.071 Qmax + 4.672 SRWm + 3.638 TCC – 0.163 SRAa – $3.060.10^{-4}$ RAR + 0.055 BARe + 0.001 CAR – 4.108 TCR – 17.914 CRR + 6.457 SFCe – 0.184 SRAm	0.57	0.180*	11.26
	WA 2	48.846 – 0.034 Qmax + 3.800 SRWm – 0.359 TCC	0.48	0.274*	11.15
	WA 3	24.339 – 0.021 Qmax + 2.501 SRWe	0.34	0.454*	12.23

*insignificant correlation as p>0.05

Table 5-14 Correlation analysis results for human smoothness, softness and warmth vs FTT full data models predictions applied to the means

		Model	Pearson's R	p-value	RMSE
smoothness	SMF 1	2.620 – 0.152 SRAe + 2.360 SRWm + 0.001 CAR_comp – 0.076 SRAa + 9.691 SFCe _comp	0.96	<0.001	2.04
	SMF 2	3.599 – 0.193 SRAm + 2.492 SRWm + $6.970.10^{-4}$ CAR_comp + $6.500.10^{-5}$ RAR _comp + 6.162 SFCm – 2.226 CRR_comp	0.96	0.001	2.18
	SMF 3	8.660 – 0.201 SRAe_comp + 2.698 SRWm – 0.072 SRAa	0.94	0.001	2.05
softness	SOF 1	25.440 – 0.007 BWa + 8.984 SFCe – 0.015 Qmax - 4.089 SFCa + 0.900 SRWa_comp – 0.092 TCR - 0.042 SRAe	0.85	0.018	2.71
	SOF 2	28.935 – 0.006 BWa - 0.016 Qmax – 0.407	0.80	0.032	3.00

		TCR + 1.158 SRWm – 0.076 SRAm + 2.618 CRR + 3.656 SFCm – 53.072 RRD + 30.069 T_comp			
	SOF 3	29.142 – 0.005 BWa_comp – 0.016 Qmax _comp – 0.075 SRAm + 1.253 SRWm – 0.007 CW_comp + 4.639 SFCm + $1.860.10^{-4}$ CAR_comp – 0.622 TCR_comp + 49.731 T_comp + 0.010 BARe_comp	0.79	0.036	2.83
	SOF 4	35.148 - 0.008 BWm – 0.024 Qmax_comp + 6.609 SFCm – 0.006 CW_comp - 0.063 SRAm + 0.755 SRWm + $1.850.10^{-4}$ CAR _comp	0.63	0.127*	3.60
warmth	WAF 1	47.343 – 0.033 Qmax – 0.004 BWa + 2.091 SRWm – 0.159 TCR – 0.103 SRAm – $4.900.10^{-5}$ RAR_comp + 0.020 BARm	0.46	0.302*	12.58
	WAF 2	50.825 – 0.036 Qmax_comp + 2.382 SRWm – 0.210 TCC_comp – 0.097 SRAm – $6.000.10^{-5}$ RAR_comp + 28.238 RCD_comp	0.61	0.144*	11.15
	WAF 3	21.361 – 0.017 Qmax_comp + 1.483 SRWe _comp – 0.003 BWa + 3.961 SFCe	0.33	0.463*	13.27

*insignificant correlation as p>0.05

All new smoothness models show an excellent prediction with $R \geq 0.89$ but the full data models, SMF 1 and SMF 2 perform better than that of mean values. SM 2 and SMF 2 which only contain surface roughness indices (SRA, SRW) give the best prediction to smoothness properties. The smoothness models error given by the RMSE value is considerably lower as compared to that of softness and warmth. For softness, the models which contain more number of indices in them show a better prediction, so SO 1 and SOF 1. It can be seen that here mean data models are better correlated with the actual human assessment data, indicated by a higher Pearson's R value. Also, SO 3 and SO 4 models which contain only bending indices yield $R>0.8$, indicating still a strong correlation between the prediction and the human assessment value. The correlation for SO 2 is insignificant as $p>0.05$, and also a higher RMSE compared to the other softness models. For warmth, the correlation is all insignificant for all models although the R value shows a low to moderate relationship. RMSE values are also very big numbers, showing a poor fit of the correlation to the actual data from human assessment. As no models were able to give strong correlations for the warmth attribute, we have to consider them wrong. The touch alteration due to washing process must have given different ways of guiding haptic sensation. Hence, the new warmth models are not good predictors for the washed fabrics.

A further investigation on the subjectively tested set of 5× washes found that warmth is positively correlated with RCD, and negatively with TCC, in which a specific model of warmth 10.177 + 325.500 RCD – 0.452 TCC with adjusted R^2=0.63 could be generated from the mean data of FTT indices, that also combined with the previous data from 0× wash. This new model is assigned as WA 4. Thus, in this model we could see that Qmax is no longer selected, since it corresponds most towards RCD, as the first term picked up by the model. RCD is 1/CAR, but in the WA 1 model, only CAR appears as the seventh term. TCC is also included in WA 1 model as the third term. We need to conclude that washing affected Qmax in a way that is not consistent with how warmth perception was influenced by washing.

The human assessment data were also exercised on the FTT reconstructed models to obtain how far these models deviate from the actual human values as opposed to our suggested predictive models. From this computation, the FTT full model error for smoothness, softness and warmth is (5.31, 4.92, 14.12) and for the reduced FTT model as given in Table 2-3 (Chapter 2), the RMSE is (5.05, 4.47, 14.75), also shown in Table 5-15 below, which indicates the standard FTT model errors are much higher (>100% more for smoothness and softness) than the errors with the new models. The acceptable RMSE values for the new models are three at the highest, hence the deviation is greater in the FTT models which reaffirms that the models are also unable to correctly predict the touch sensation given by the washed fabric set, similarly to the unwashed set.

Table 5-15 FTT reconstructed model error

	RMSE		
	smoothness	**softness**	**warmth**
FTT full data model	5.31	4.92	14.12
FTT reduced model	5.05	4.47	14.75

The best models should be chosen based on two factors, i. high correlation or adjusted R^2 value, and ii. low model error. Hence, we suggest SMF 1 as the best model for smoothness and SO 1 for softness. The relationship of SMF 1 and SO 1 models with human assessment data are visualized in the plots in Figure 5-13. Both models have R>0.9 and RMSE<3. The predictive power of the best models (SMF 1 and SO 1) and also the FTT reduced models is visualized in Figure 5-14. The new models show a better prediction compared to the FTT models, as shown by the closer regression line towards the actual human values.

No good model was found for warmth though in Table 5-2 we have warmth index from 7% to 65%, so a large range of covered index. In our subjective testing, the warmth results deviate by a large factor at ± 4, while we would except in testing of materials that have clear characteristics to have ± 1 or max ± 2. This indicates the samples are probably too closely related for humans to distinguish, and a wider sample set is needed. This also comes forward when combining the new panel results with the old, after which woven PET 5× washed is assigned a warmth panel scale value of 30, far outside the range of 1-10 considered for warmth evaluation or the original sample set. As the fabrics were tested in two separate batches, two reference samples from the first batch were included in the assessment with the second batch of samples. This is done to link the two batches through feature scaling normalization technique as mentioned in Chapter 3. The chosen reference fabrics are the warmest and coolest amongst the first batch samples, taken from the mean value, although the deviation amongst the panels are high. As the reference are highly deviated, and the evaluation of warmth for the second set of fabrics are also highly deviated among the panel members, the normalized scales stretched wider up to 30 in our case. This is undesirable for a good test setup, and also indicates the original batch had indeed a warmth feel which was too close related for the intended use.

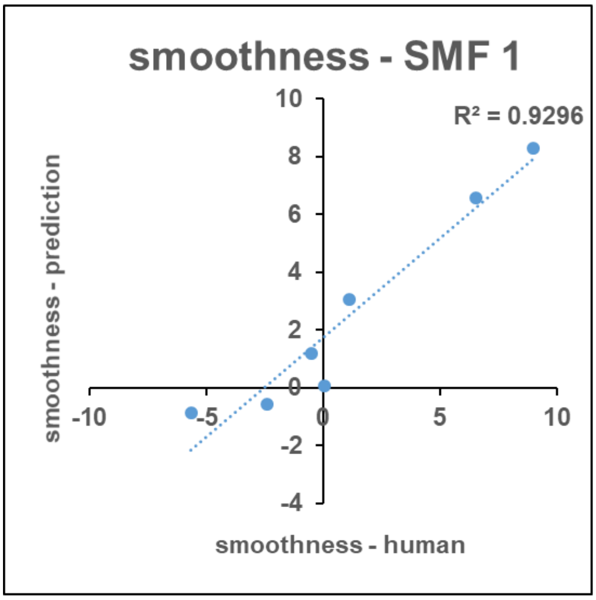
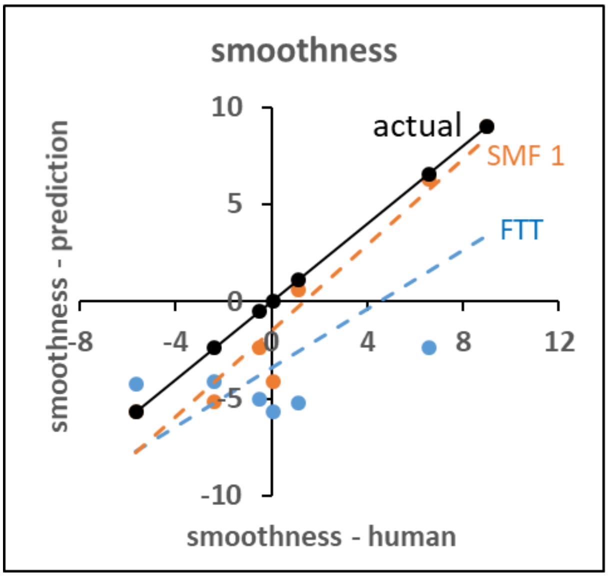


Figure 5-13 Scatter plots showing strong positive correlation between predictive models and human assessment data; left – SMF 1 model prediction for smoothness, right – SO 1 model prediction for softness.



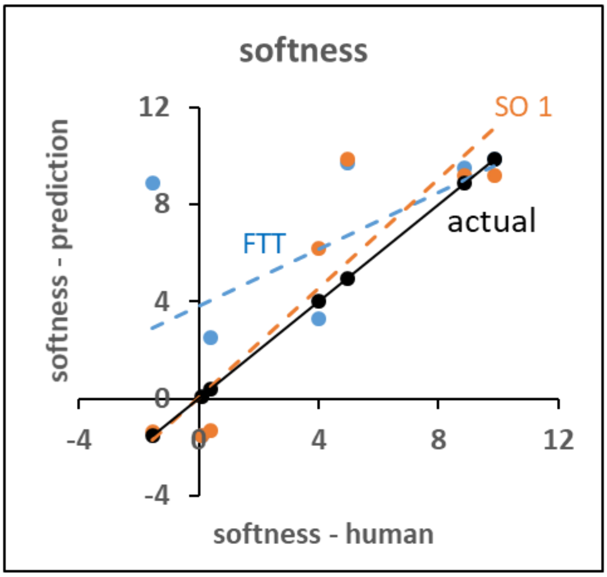


Figure 5-14 Predictive power comparisons between the best new models and FTT reduced models.

Insights into warmth might be reached by comparing the samples treated with 0×, 1× and 5× washes to see what indices changed, and how the subjective testing changed due to these observed changes. Human assessment was not conducted on 1× wash samples, only for 0× wash and 5× washes as illustrated in Figure 5-15. Nevertheless, as mentioned earlier, number of washing cycles affects six indices i.e. BARm, TCR, SFCm, Qmax, BWm, and SRWm. The warmth model for the new fabrics consists of two terms i.e. RCD and TCC. TCC and TCR are highly correlated, hence, it seems that the changes in TCC or TCR due to washing influenced the warmth sensation of fabrics. Generally, TCC or TCR increases with the increase in the number of washes, but it reduces the BARm. Figure 5-16 illustrates the FTT results of 0×, 1×

and 5× washes for the terms. Example of fingerprints of a fabric i.e. PET for 0×, 1× and 5× washes are shown in Figure 5-17. Fabrics with 0× and 1× wash did not change much for BARm, BWm, TCR, and CRR. But CRR and BARm are lower for 5× washes. Comparison of the predictive power of the new warmth model WA 4, the FTT reduced model and the actual value from human assessment is illustrated in Figure 5-18. The RMSE for WA 4 model is 7.42. Although it is lower than that of FTT model, the value is still very high.

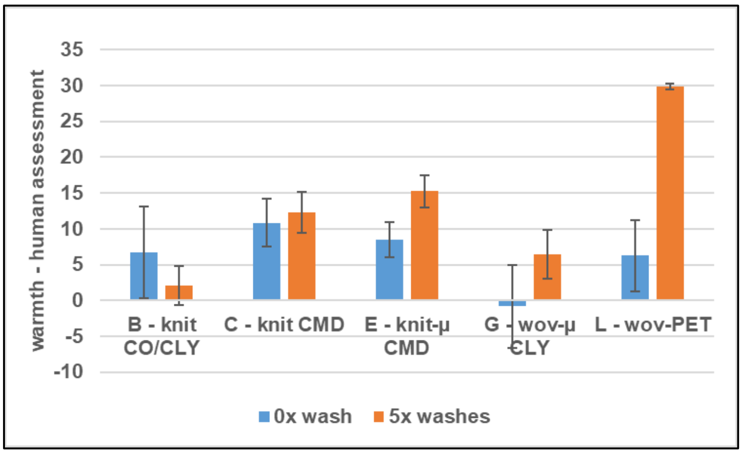


Figure 5-15 Human assessment results for warmth for 0× and 5× washes

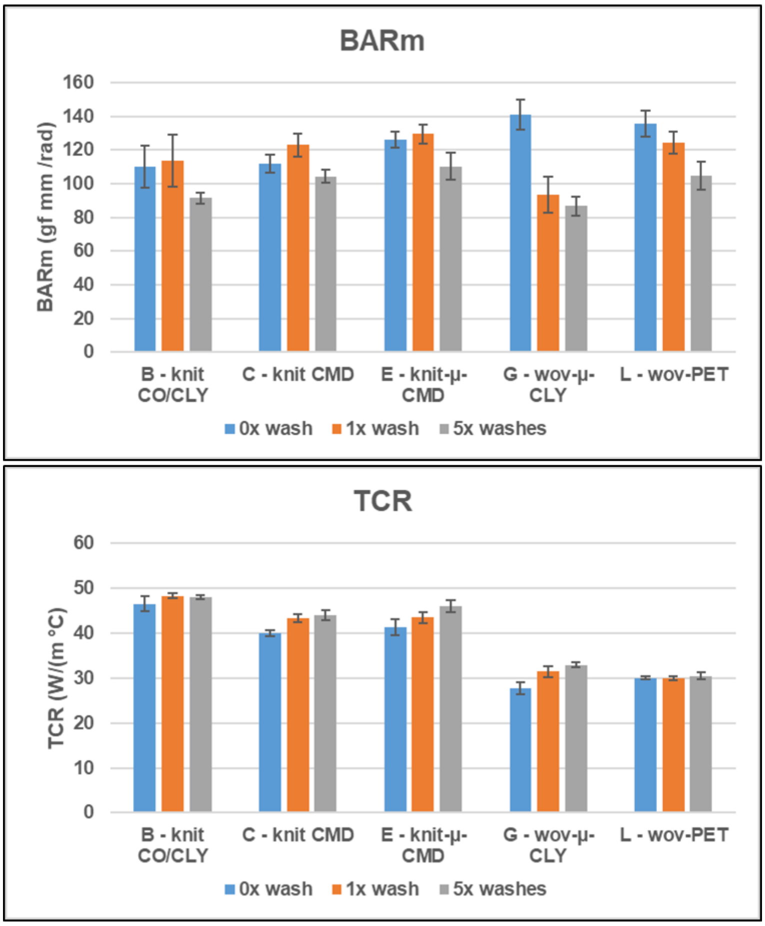


Figure 5-16 Effects of number of washes on BARm and TCR indices

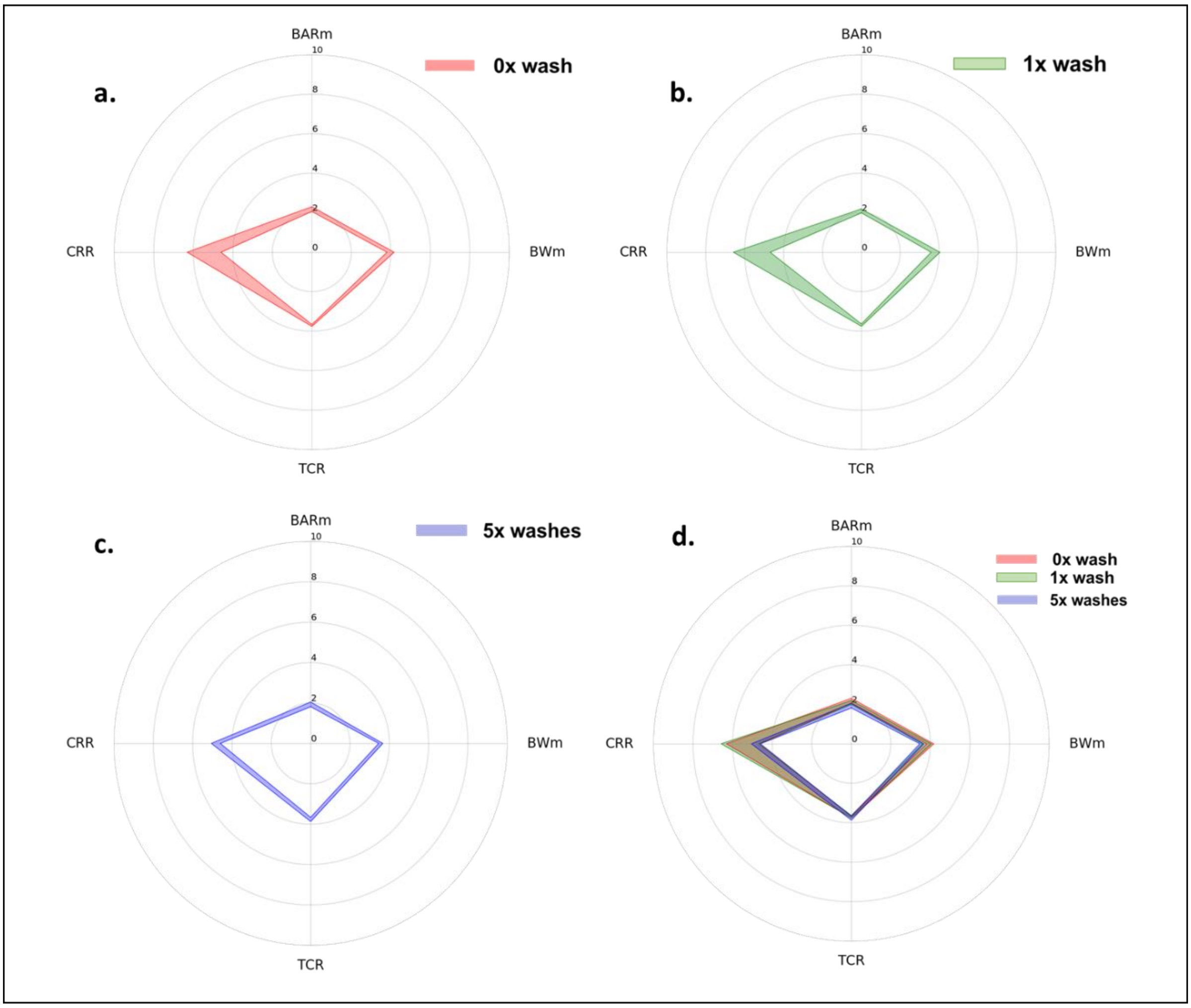


Figure 5-17 Fingerprints of PET woven fabrics for several FTT indices; a) 0× wash, b) 1×, c) 5× washes, and d) combine plots of 0×, 1× and 5× washes.

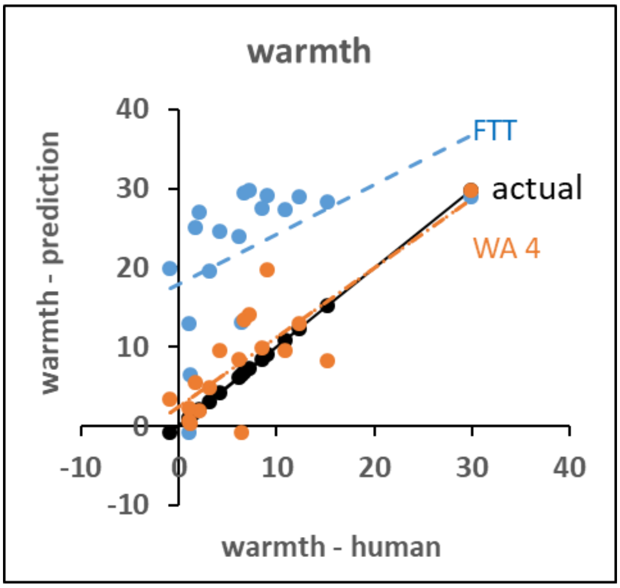


Figure 5-18 Predictive power comparisons between the new warmth model WA 4 and FTT reduced models

5.6 Conclusion

Since the FTT is meant to measure the fabric properties and make predictions on the fabric handle based on the measurements, the prediction models of the FTT were analysed. An experiment on 13 fabrics was conducted by testing them in two ways i.e. subjectively by human panels and objectively by FTT itself. The results from both methods were compared and they showed some discrepancies, meaning that the predictive comfort model of FTT were lacking. Thus, several new models were generated based on the fabrics to account for differences in indices picked-up by them and also that of FTT model reconstructed earlier.

The newly introduced models were validated by giving them a new set of data from the same type of fabrics, after enduring some wash treatments. Based on the Pearson's R correlation and RMSE, it is found that with the changes in characteristics of the fabrics after washing, the new comfort values are best modelled with SMF 1 for smoothness and SO 1 for softness. Smoothness was found to correlate best with surface roughness indices i.e. SRA and SRW. Hence, the selected best model, SMF 1 picked-up these indices as the first two out of six terms included. Other indices listed in SMF 1 are CAR, RAR and CRR from the compression module and SFC from the surface module. For softness, bending indices i.e. BAR and BW dominate as the first two terms picked-up by the best selected model, SO 1, before other seven terms. SO 1 has at least one index from each module.

The new proposed warmth models seem to associate with thermal index Qmax and also roughness. The model gives a perfect fit (R^2=1.0) with a total of 11 terms for the mean value of the 13 fabrics. However, the models are not valid when tested with the validation set of fabrics which suggest two things; i. the new models, as well as the FTT models are only suitable for specified type and condition of fabrics, and ii. the human panel are unable to discern the warm-cool behaviour of the fabrics through the conducted method, that is, the warmth scale must be compressed in the sense that our range of 1 to 10 used now in Fig. 3-7, should be rather a scale 3-4, indicating all samples are almost equally warm and closely related in warmth comfort. Therefore, a further study emphasizing on the tactile-thermal behaviour and haptic perception of warmth is recommended for future work.

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6

Conclusions

It always seems impossible until it is done.

Nelson Mandela

This thesis conveys over six chapters the work which aims to **evaluate the tactile response to haptic sensations on clothing fabrics.** In **Chapter 1**, an overview of the topic was presented. Also, the motivation for this research, as well as the aim and objective were mentioned. Having chosen Fabric Touch Tester (FTT) as the objective tool to measure fabric handle, the reasons for that were stated in **Chapter 2**. To assess the reliability of it, the single index measurement of the device was compared with that of standard methods. In **Chapter 3**, the developed subjective assessment of fabric handle was discussed and an extension was suggested to the protocol in which large number of samples can be better assessed and compared. The aim of doing objective testing and subjective testing on fabric handle is to link the two via models. The existing status of predictive models was given in **Chapter 4** where the prediction models on fabric touch sensations from previous studies were conveyed. In addition to that, an expansion of the biomechanical model which was started by another researcher, was presented. It was found that the models were often lacking, requiring a deep study in approaches to improve the predictive modelling. This was considered in **Chapter 5**, which described the extensive experiments of subjective and objective evaluations and presented the statistical models developed from the experiments, and the lessons we learn from them. Lastly, in this **Chapter 6**, the conclusions from the works are reported, and the recommendation on further work are suggested.

The following conclusions can be derived from the work that has been done.

i. The emergence of Fabric Touch Tester (FTT) brings simplicity to the testing protocol of the comfort properties of clothing fabrics.

ii. The results from the single index measurement of FTT can be associated with the common/standard methods. However, the use of FTT to substitute the measurement from standard methods is discouraged.

iii. As the subjective assessment involves humans, the protocol should be carefully observed especially when the results are used for the prediction modelling of a device. A careful selection of test samples, as well as the procedures to measure a large sample size should take into account the human factors e.g. fatigue and loss of focus.

iv. The suggested comprehensive approach to measure subjective fabric handle offers a better alternative to measure a large size of samples, which considers the human factors mentioned above.

v. To date, it can be said that FTT is the one and only device of its kind that can measure handle properties of fabric within five minutes per sample, comprehensively for warp and weft, outside and inside. However, the FTT predictive comfort models could not catch the differences of the materials as reported by panel members in this thesis. This might be due to the limited range of fabrics tested by the manufacturer to generate the comfort models.

vi. FTT is mainly useful for common clothing fabrics. Technical fabrics such as spacer or fabrics with non-homogenous surfaces are not suitable to be tested by the device.

vii. New comfort models were suggested for smoothness and softness which give a better prediction on the samples. The models were validated by the same set of fabrics after being given washing treatment for five cycles in order to see how a single property changes the characteristics and influences the touch sensation. Based on high fitting with the actual human data and low model error, SMF 1 and SO 1 models were selected as the best models for smoothness and softness, respectively. Smoothness model, SMF 1 is largely affected by SRA and SRW indices from surface roughness measurement of FTT. For softness, bending indices BAR and BW are the dominant indices in SO 1.

viii. Nevertheless, warmth models remain invalid when they are tested with other sets of fabrics, indicating a lack of understanding or validity of the warmth testing.

This research opens more doors for exploration. Further works can be done in the following areas;

i. The measurement method in FTT is proven to well-associated with the common/ standard methods. However, since the measurement methods used are different, the robustness of the method in FTT can be further investigated.

ii. Improvements to the FTT in future versions would be welcome, mostly better accuracy, better friction testing, and handling of abnormal situations like infinite RAR or zero SRW. Measuring elasticity, which is missing in the FTT device, but present in e.g. KES-FB, could be useful also for fabric handle assessment.

iii. Upon the understanding on the factors that govern the tactile behaviour through the developed statistical model, advanced prediction methods e.g. neural network and fuzzy logic, can be tested out and further explored.

iv. By using the suggested method of subjective evaluation mentioned in Chapter 3, more samples can be included. As much as the idea that an increment of the samples can generate a better model, at least two things should be considered, i. variability of the samples i.e. the sample should not only add to the quantity, but also give more variability in the pool of samples, ii. re-manufacturing possibility of the samples used in constructing of the models, hence, the characteristics of the samples which are used in modelling the fabric handle should be made available.

v. The biomechanical modelling approach seems feasible with finite-element method. It would be more realistic to implement it with sufficient material and geometrical data from the real human. For that, a cross-discipline study between textile engineering and human-physiological based field are needed. The current study is required to correctly identify what changes in fabric parameters lead to which human fabric feel changes. This information can now be matched with the effect of the same fabric parameters on human skin as obtained from a biomechanical model. The big variability within a sample type observed in the fabric data measured with the FTT must however be better understood, so as to understand how fabrics are best represented for use in a biomechanical model.

vi. We considered homogeneously textured fabrics. The effect of non-homogeneously textured fabrics, and how it changes the perceived fabric handle, is an open question. Some combinations of fabrics completely alter the overall evaluation of a garment, indicating more than the single local fabric properties of important. These fabrics cannot be measured easily in the current testing devices, and require new methods to be developed.

vii. An insight on warmth perception needs to be further explored e.g. develop a new protocol for human measurement of warmth to grasp more meaningful information with less deviation among panel members.

In this research we have come a long way in developing methods to improve the fabric handle research. We could validate a new fast objective testing device, we developed improved subjective tests that allows us to extract the maximum of information when combined with the objective testing. We suggest on a sample set new models for active softness, smoothness and warmth, and tested these with a validation experiment. Nevertheless, much more research will be needed before fabric handle is fully understood. We sincerely hope the reader has a better handle on how this research can proceed.

List of publications

The findings for this research were disseminated through publications and presentations in several international journals and conferences.

Articles in academic journals

Binti Haji Musa, A., Malengier, B., Vasile, S., & Van Langenhove, L. (2019). A comprehensive approach for human hand evaluation of split or large set of fabrics. Textile Research Journal, first published 24 February 2019.

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